

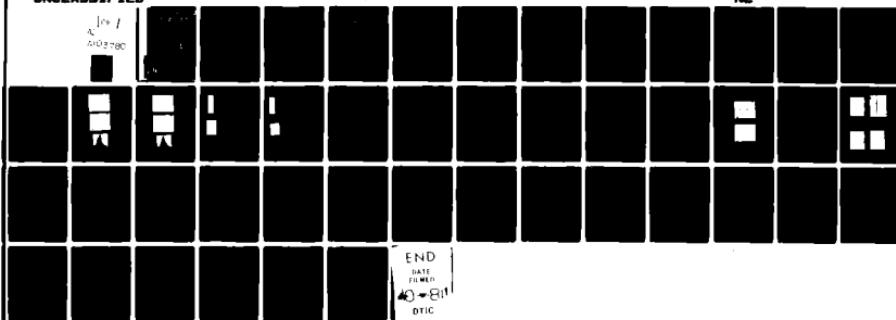
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ULTRASONIC TRANSDUCER PERFORMANCE REQUIREMENTS. PHASE III.(U)
AUG 81 H KWUN, G L BURKHARDT, C M TELLER F41608-79-D-A011

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ULTRASONIC TRANSDUCER PERFORMANCE REQUIREMENTS – PHASE III

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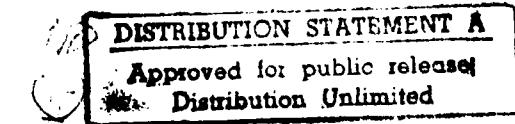
FINAL ENGINEERING REPORT

**Contract No. F41608-79-D-A011-0002
SwRI Project No. 15-5711**



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
	AD-A103 780	
4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED	
Ultrasonic Transducer Performance Requirements, Phase III.	Final Engineering Report. June 1979 - August 1981	
7. AUTHOR(s) Hegeon/Kwun Gary L. Burkhardt Cecil M. Teller	6. PERFORMING ORG. REPORT NUMBER	
	SwRI Project No. 15-5711	
8. PERFORMING ORGANIZATION NAME AND ADDRESS Southwest Research Institute 6220 Culebra Road San Antonio, Texas 78284	9. CONTRACT OR GRANT NUMBER(s)	
	15 F41608-79-D-A011-0002	
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Air Force Nondestructive Analysis Branch San Antonio, ALC/MMEI Kelly Air Force Base, Texas 78241	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12. REPORT DATE Aug 1981	
	13. NUMBER OF PAGES 38	
	15. SECURITY CLASS. (for this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; Distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Nondestructive inspection, ultrasonic transducers, transducer performance parameters, simplified test methods, acceptance limits.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Simplified test methods are presented for assessing performance parameters of 5 and 10 MHz contact type ultrasonic transducers used in Air Force field and depot level nondestructive inspection. Ultrasonic transducer performance parameters covered are: Overall Appearance, Beam Exit Point, Beam Angle, Skew Angle, Beam Divergence Angle, Center Frequency, Pulse Length, Dead Zone, Signal-to-Noise Ratio, and Overall System Sensitivity. Requirements are given for the ultrasonic instrument to be used for the tests. The importance of		

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ULTRASONIC TRANSDUCER PERFORMANCE REQUIREMENTS—PHASE III

by

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Garry L. Burkhardt
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FINAL ENGINEERING REPORT

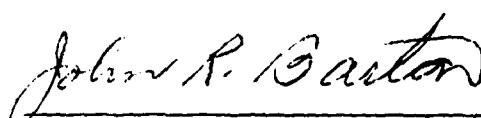
Contract No. F41608-79-D-A011-0002
SwRI Project No. 15-5711

The investigation reported in this document was requested by the U.S. Air Force Nondestructive Analysis Branch, San Antonio Air Logistics Center/MMEI; Kelly Air Force Base, Texas 78241, under Government Contract No. F41608-79-D-A011-0002; however, it does not necessarily bear the endorsement of the requesting agency.

June 1979 to August 1981

Approved for public release; distribution unlimited.

Approved:



John R. Barton, Vice President
Instrumentation Research Division

FOREWORD

This project was sponsored by San Antonio Air Logistics Center, Kelly Air Force Base, Texas, under Contract No. F41608-79-D-A011-0002. Southwest Research Institute, San Antonio, Texas, was the contractor and performed the work from June 1979 to August 1981 under technical direction provided by Mr. B. W. Boisvert and Mr. Vernon Vitterbo, Air Force Nondestructive Analysis Branch, MMEI, Kelly Air Force Base. Dr. Cecil Teller was the Project Manager and Dr. Hegeon Kwun and Mr. Gary L. Burkhardt were the Project Engineers. Acknowledgement is made to Mr. D. R. Bouressa for his technical assistance, to Mr. D. J. Krueger and Mr. A. Ramirez for preparing drawings, and to Mrs. R. F. Hogue and Mrs. D. Granados for typing the final report.

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ABSTRACT

Simplified test methods are presented for assessing performance parameters of 5 and 10 MHz contact type ultrasonic transducers used in Air Force field and depot level nondestructive inspection. Ultrasonic transducer performance parameters covered are: Overall Appearance, Beam Exit Point, Beam Angle, Skew Angle, Beam Divergence Angle, Center Frequency, Pulse Length, Dead Zone, Signal-to-Noise Ratio, and Overall System Sensitivity. Requirements are given for the ultrasonic instrument to be used for the tests. The importance of maintaining an initial excitation pulse to certain specified conditions, such as a spike or single cycle bipolar spike with duration less than 0.5 μ sec, to achieve uniformity and instrumentally unbiased test results is addressed. Methods are also described for establishing a specified initial excitation pulse by adjusting controls on the ultrasonic instrument.

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I. INTRODUCTION

Results of ultrasonic nondestructive inspection (NDI) are highly variable¹ and, consequently, the reliability of ultrasonic NDI is often low. The lack of reproducible and uniform test results can be attributed partly to variation in the performance of ultrasonic transducers employed in the inspections. In order to improve ultrasonic NDI reliability and provide improved uniformity of results, it is essential to control the performance variation of ultrasonic transducers. There are many measurable parameters which can be used for characterizing ultrasonic transducer performance; for example, center frequency, beam angle, and loop sensitivity. Since it is impractical to control all the measurable parameters, investigations^{2,3} were conducted to identify those parameters which must be controlled to achieve high reliability and uniformity of ultrasonic NDI. As a result of these investigations, preliminary test methods and specifications (acceptance limits) for ultrasonic transducer performance parameters were developed³.

The objectives of the present project were to develop simplified test methods for determining and verifying acceptance performance of 5 and 10 MHz contact type transducers used in Air Force field and depot level NDI, based on the results of the aforementioned investigations. The long range goal of this project is to improve reliability and uniformity in ultrasonic NDI applied at Air Force field and depot levels. This project covers the requirements to establish simplified field/depot level test methods for satisfactory determination of ultrasonic transducer performance parameters.

II. SIMPLIFIED TEST METHODS FOR ULTRASONIC TRANSDUCER PERFORMANCE PARAMETERS

In Section II.A.1., a general description of ultrasonic pulse-echo instruments used in ultrasonic nondestructive inspection (NDI) is given. In Section II.A.2., the requirements of an ultrasonic instrument used for testing transducer performance parameters are described. Since the performance of a transducer is greatly influenced by the ultrasonic instrument employed or by the setting of the controls on a given ultrasonic instrument, in Section II.A.3. the initial set-up of the ultrasonic instrument is specified to minimize the influence of the instrument on the performance of the transducer.

In Section II.B., simplified test methods for ultrasonic transducer parameters are described. In evaluating transducer parameters, the conventional pulse-echo method is used exclusively.

A. ULTRASONIC INSTRUMENT

1. General

Ultrasonic pulse-echo instruments perform the generation, reception, and amplification of electrical pulses, as well as the display of these electrical pulses in terms of their amplitude and time of occurrence. An ultrasonic instrument can be divided into three basic units: pulser, receiver, and display.

The pulser generates the electrical pulses which excite the ultrasonic transducer which, in turn, converts some of the applied electrical signal into mechanical vibrational signal (i.e., a sound wave). The pulser is usually provided with controls for the pulse duration (or pulse length; sometimes designated as "damping"), pulse tuning (for adjusting the pulse frequency), and pulse repetition rate (for adjusting the rate of the electrical pulse generation per unit time).

When a sound wave strikes the ultrasonic transducer, part of the sound wave is transformed into an electrical signal by the transducer. The receiver amplifies this rf (radio frequency) electrical signal. The signal is then usually rectified in the receiver and is then supplied to a display. Receivers of some ultrasonic instruments can supply both the rectified signals as well as the unrectified signals to the display. The receiver is usually provided with controls for signal amplification (usually called "sensitivity"; other terms in common use are "attenuation" or "gain"), and/or filtering (for shaping the rectified video signal by smoothing out ripples on the signal).

The display visually presents the electrical pulses or signals from the receiver on a cathode ray tube (CRT) as a function of their amplitudes and time of occurrence. The display has sweep speed as well as sweep delay controls. Depending on the signals supplied by the receiver, either rectified video signals or unrectified rf-signals are displayed.

As described above, the ultrasonic signals are generated, detected and displayed by electrical means. Therefore, the results of ultrasonic NDI or the performance of an ultrasonic transducer are subject to change depending on

the electrical characteristics of the instrument employed. (Note that the electrical characteristics of a given instrument vary as the control settings of the instrument are changed.) Nonuniform test results obtained in ultrasonic NDI are partly due to variations in the electrical characteristics of the ultrasonic instruments, as well as partly due to variations in the performance of each ultrasonic transducer. In order to assess the performance of the ultrasonic transducers as independently as possible of the ultrasonic instrument employed, the electrical characteristics of the instrument must be specified and controlled, and the characteristics of the initial transducer excitation such as the shape and the duration of the initial excitation pulse, must be kept as constant as practical.

2. Requirements

To assess the performance of ultrasonic transducers, the ultrasonic instrument employed must have at least the following characteristics:

- (a) Pulser - be capable of generating an initial excitation pulse of duration less than or equal to 0.5 μ sec and a unipolar voltage (base to peak) of at least 200 V into a 50 ohm external resistive load (the duration of the pulse is defined as the time interval over which the pulse amplitude exceeds 10% of its maximum amplitude);
- (b) Receiver - have either a wide band or a narrow band receiver operable at 5 and 10 MHz (peak response frequency of the narrow band receiver shall be within 5% of the nominal operating frequency of the receiver), have a calibrated receiver gain (or attenuation) of at least 60 dB dynamic range which is adjustable in steps no greater than 2 dB, and be capable of converting rf-echo signals to rectified video signals without extending the apparent pulse length of the rectified signals, T_b in Fig. 1-b, by more than 10% of the actual pulse length of the rf-signal, T_a in Fig. 1-a, where pulse length is defined as the time interval over which the pulse amplitude exceeds 10% of its maximum amplitude [i.e., $(T_b - T_a)/T_a$ must not exceed 0.1];
- (c) Display - have a CRT display with vertical and horizontal linearity within \pm 5%, have calibrated sweep speeds of at least 100, 50, 20, 10, 5, 2, 1 and 0.5 μ sec per division, and have a sweep delay which is continuously adjustable over a range of at least 100 μ sec.

The horizontal and vertical linearities of the CRT display can be calibrated by using appropriate reference blocks, such as an IIW block, as described in Technical Manual T.O. 33B-1-1, "Nondestructive Inspection Method" (1979) or in ASTM E317, "Standard Recommended Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Systems without the Use of Electronic Measurement Instruments" (1979). Also, the receiver gain can be calibrated with the use of a precision external step attenuator as described in ASTM E317.

However, for accurate calibration or verification of the ultrasonic instrument characteristics such as the amplitude of the initial excitation pulse, receiver gain, and sweep speed, laboratory electronic instruments such as an oscilloscope, a signal generator, and a calibrated time mark generator

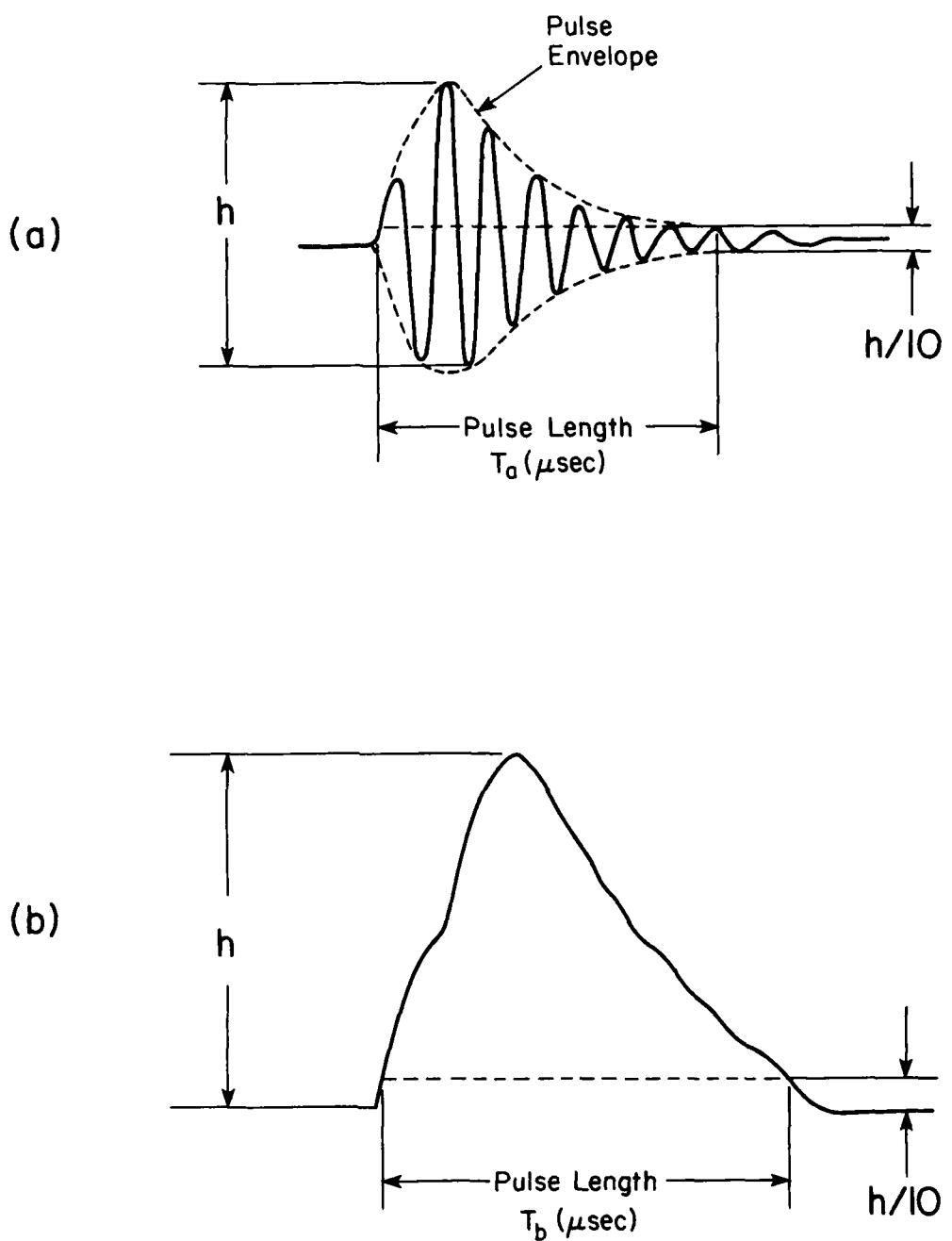


FIGURE 1. DEFINITION OF PULSE LENGTH
a) rf signal and b) corresponding
rectified video signal

are required. Therefore, the verification of these characteristics may not be readily performed in a field level NDI shop. A periodic check-up and calibration of the ultrasonic instrument in a depot level NDI shop with the laboratory electronic equipment is necessary as a part of the regular instrument maintenance schedule.

3. Initial Set-Up

As already mentioned, the performance of a transducer and consequently the results of ultrasonic NDI are influenced by the control settings of the instrument. Because of the interaction between the instrument and the transducer, the shape of the initial excitation pulse applied to the transducer varies depending on the electrical impedance of the transducer and the control settings on the instrument. Since a transducer generates sound in response to the initial excitation pulse, variation in the initial excitation pulse can result in the nonuniform test results when measuring the characteristic parameters of a given transducer.

Figures 2 and 3 illustrate how the shape of an rf-echo signal of a transducer and its frequency spectrum are affected by the initial excitation pulse shape. (These were measured using the arrangement shown in Fig. 8. with a 10X oscilloscope probe.) The two initial excitation pulses shown in Figs. 2 and 3 were obtained with the same 5 MHz-45° transducer by changing the control settings of the ultrasonic instrument. Note that significantly different initial excitation pulse shapes are obtained by varying only the pulser controls. The longer initial excitation pulse such as shown in Fig. 2 will be referred to as type-A and the shorter initial excitation pulse such as shown in Fig. 3 will be referred to as type-B. The corresponding rf-echo signals were obtained from an aluminum semi-circle block of 6.35 cm (2.5 in.) radius and 1.59 cm (0.625 in.) thickness, and these rf-signals are the first echoes from the concave circular surface. The position of the transducer was held fixed throughout the measurements. Due to the change in the initial excitation pulses, the same transducer shows very different rf-echo signals and, consequently, very different frequency spectra.

Changes in the initial excitation pulse can also considerably alter the beam profiles as well as the distance-amplitude curve of the generated sound. Examples of these effects are shown in Figs. 4 through 6. The beam profiles shown in Figs. 4 and 5 were obtained from 1.59 mm (0.0625 in.) diameter side-drilled holes by scanning a side-drilled hole block (Fig. 7) with a 5 MHz-45° transducer (which is different from the one used in Figs. 2 and 3). (For a detailed description of the data acquisition and analysis system for the beam characteristic measurements, refer to reference 3.) The respective initial excitation pulses as well as the rf-echo signals (obtained from the 10th side-drilled hole in Fig. 7 with transducer positioned for maximum echo amplitude) are also shown in the figures. In Fig. 6 the corresponding distance-amplitude curves thus obtained are shown. In this figure, amplitudes were normalized with respect to the amplitude (which is the maximum echo amplitude from the 8th side-drilled hole in Fig. 7) at scan position 5 in Figs. 4 and 5 for the sake of comparison. Note that the amplitude in the far field region [in this case, a distance greater than approximately 6.35 cm (2.5 in.)] decreases faster for the case of the type-B pulse shown in Fig. 5 than for the case of the type-A pulse shown in Fig. 4, which is in agreement with theory⁴.

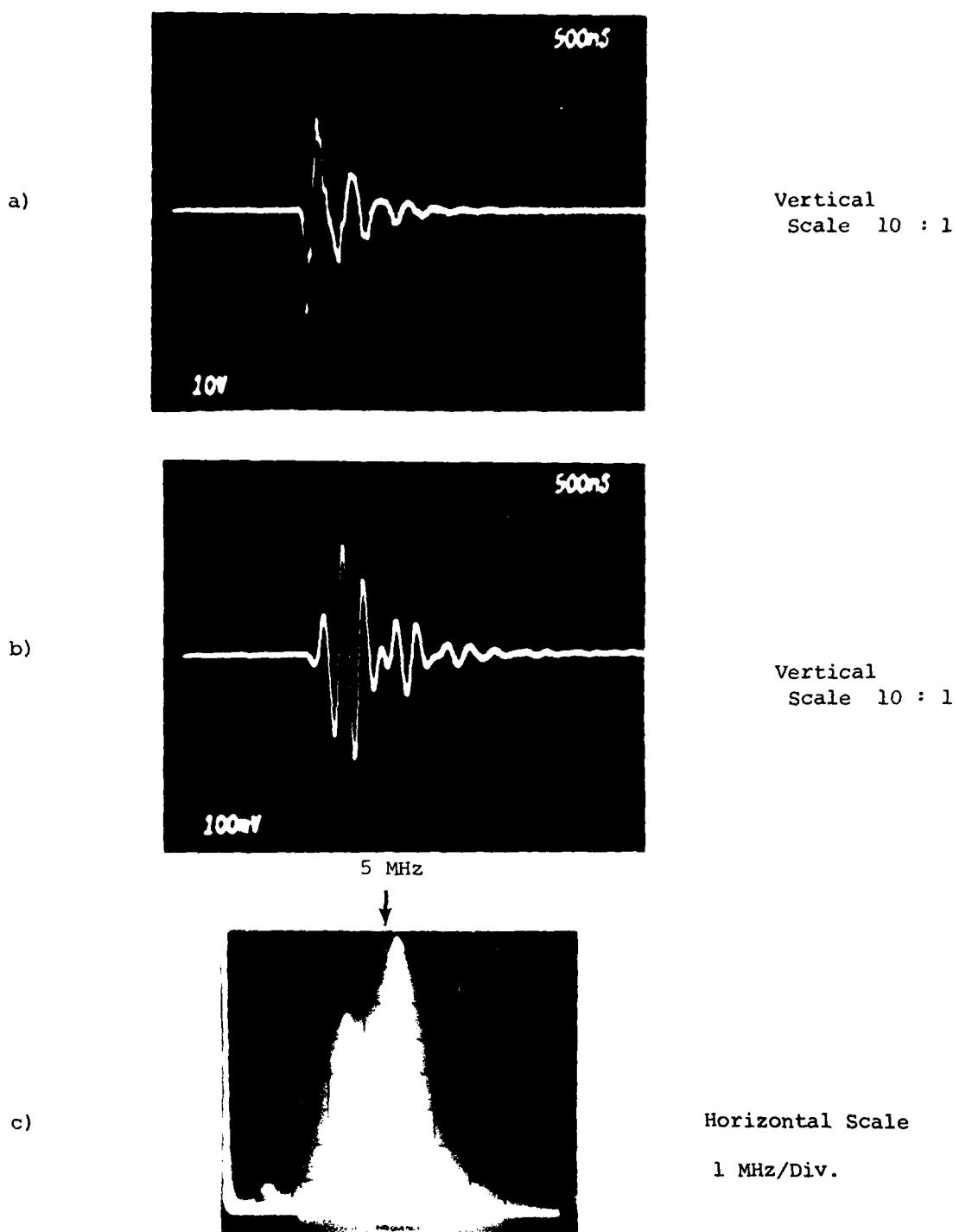


FIGURE 2. LONG INITIAL EXCITATION PULSE AND CORRESPONDING
RF-ECHO AND FREQUENCY SPECTRUM

- a) Initial Excitation Pulse, b) RF-Echo, and
- c) Frequency Spectrum (with a 5 MHz-45° Transducer)

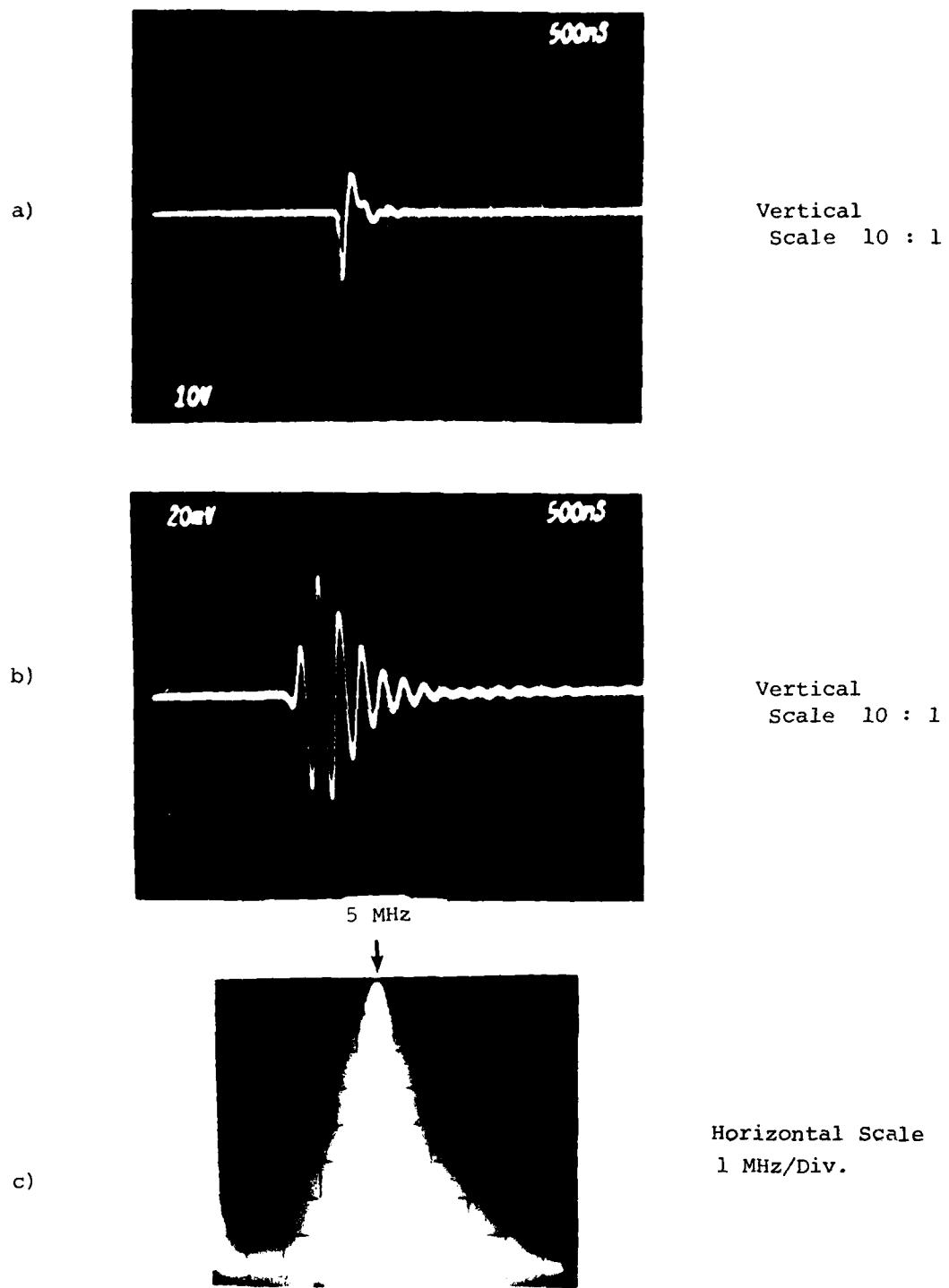


FIGURE 3. SHORT INITIAL EXCITATION PULSE AND CORRESPONDING RF-ECHO AND FREQUENCY SPECTRUM

- a) Initial excitation pulse, b) RF-echo, and
- c) Frequency spectrum (with the same transducer used in Fig. 2)

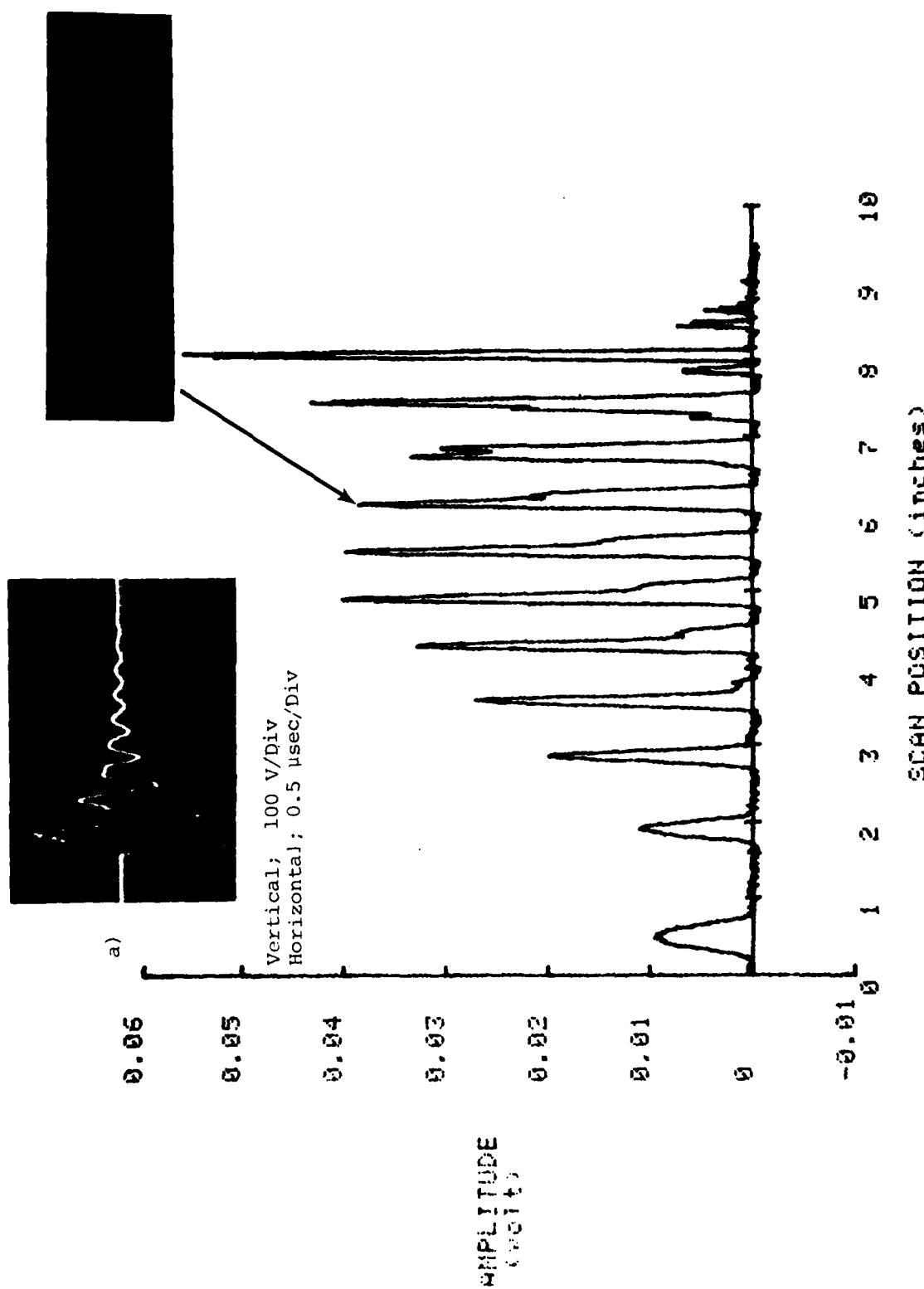


FIGURE 4. INFLUENCE OF LONG INITIAL EXCITATION PULSE ON BEAM CHARACTERISTICS
 a) Initial excitation pulse, and b) RF-echo obtained at the scan position indicated by an arrow (with a 5 MHz-45° transducer and from a side-drilled hole block shown in Fig. 7.)

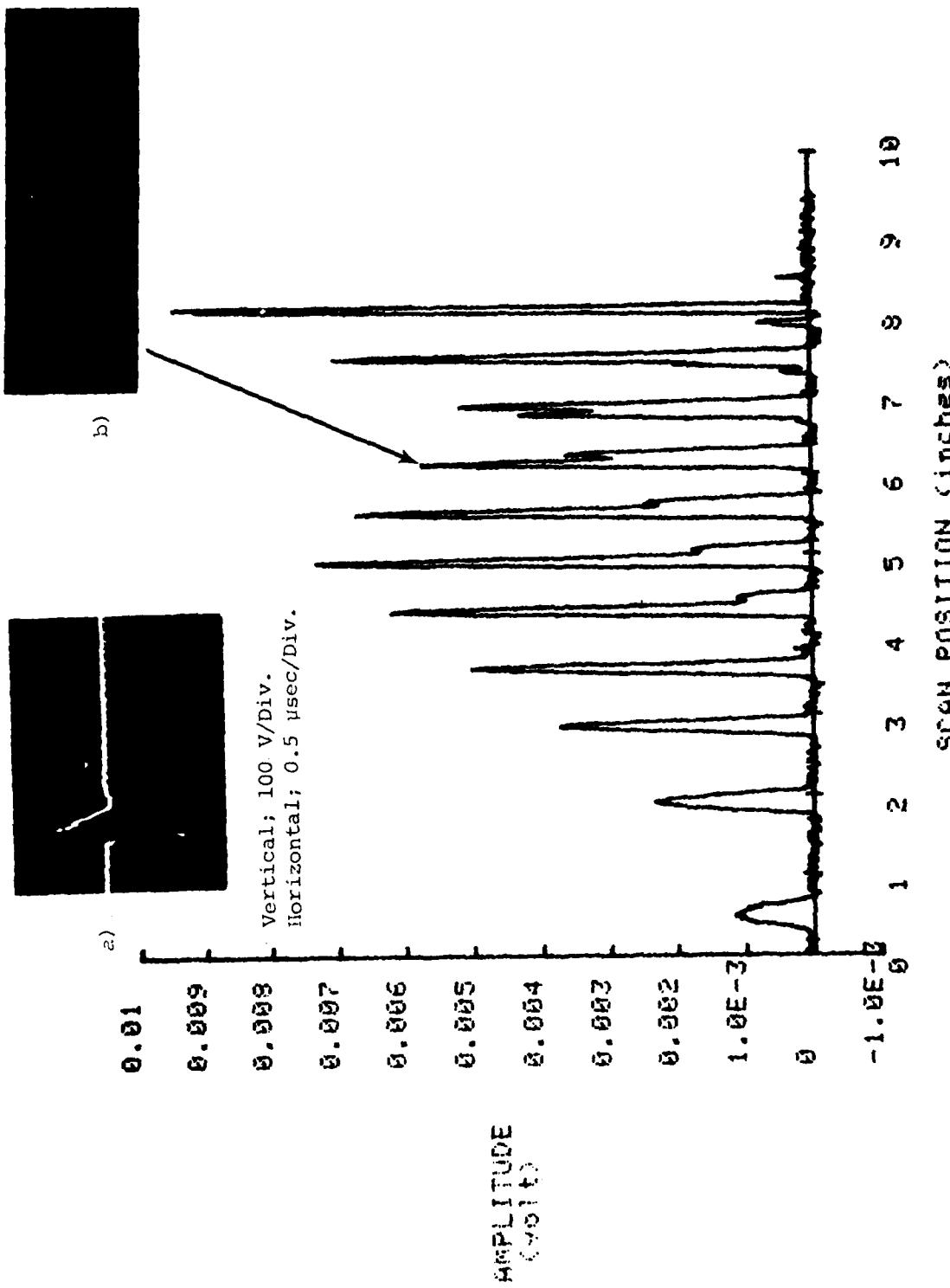


FIGURE 5. INFLUENCE OF SHORT INITIAL EXCITATION PULSE ON BEAM CHARACTERISTICS

a) Initial excitation pulse, and b) RF-echo obtained at the scan position indicated by an arrow (with the same transducer used in Fig. 4 and from a side-drilled hole block shown in Fig. 7)

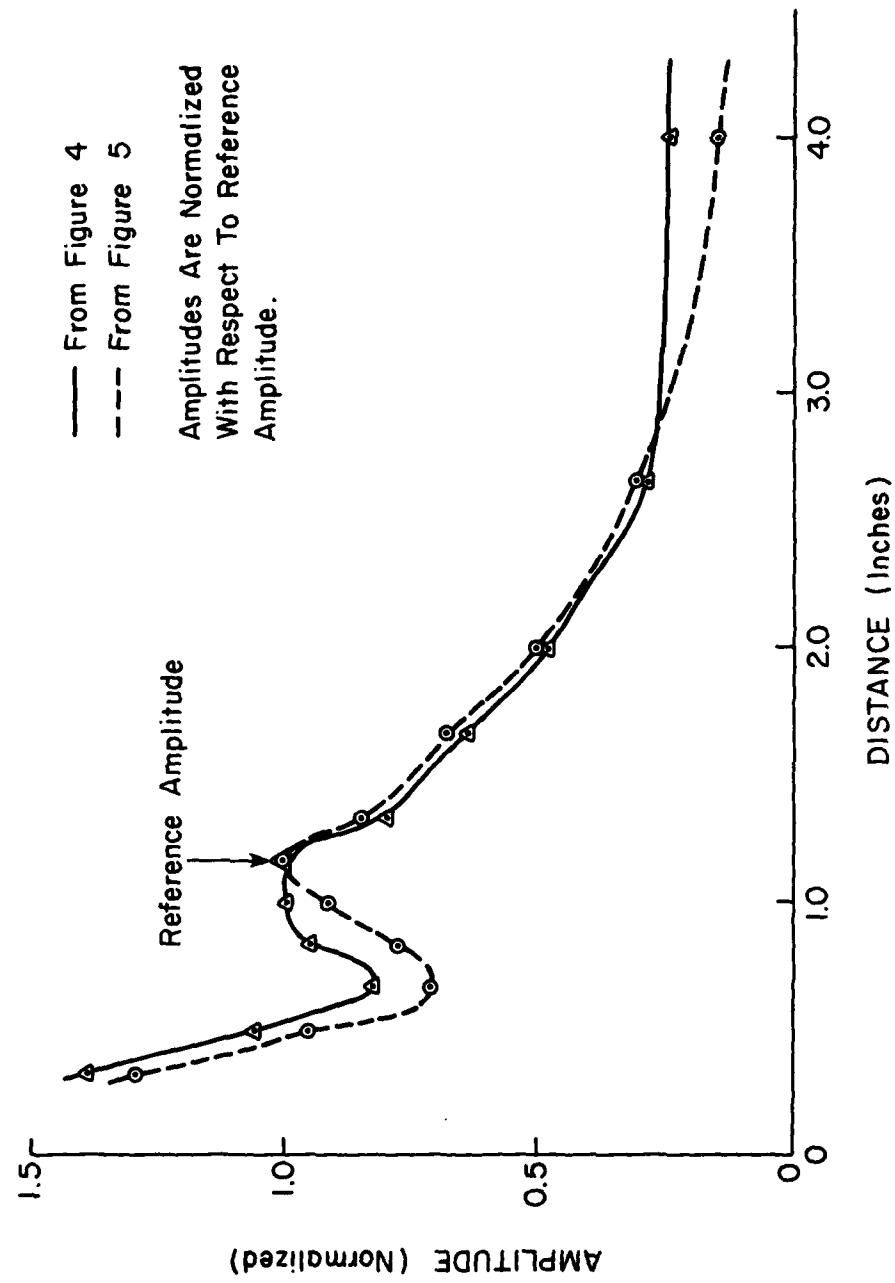
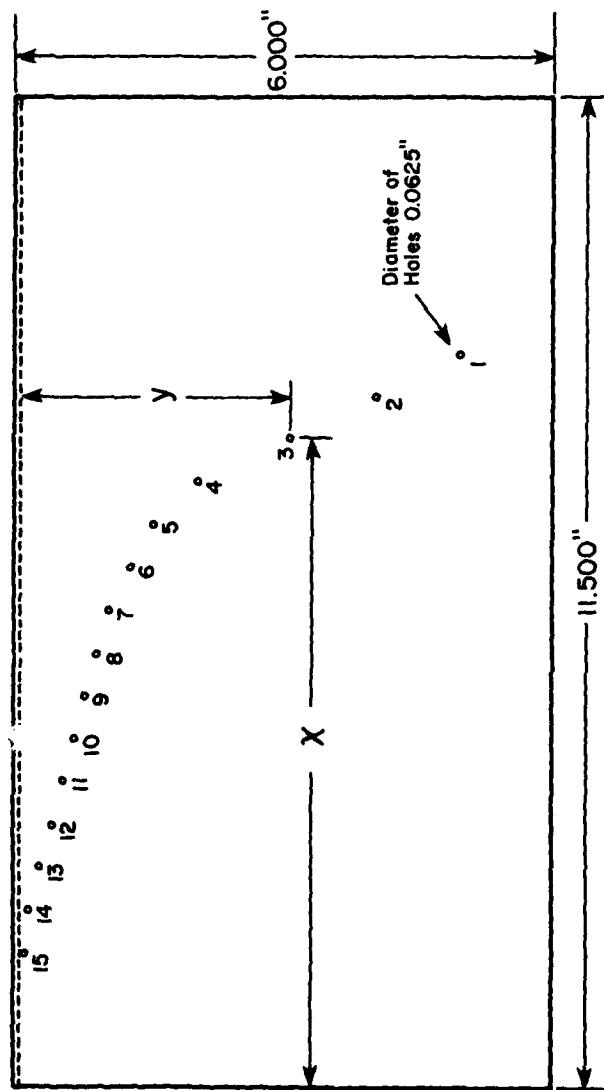


FIGURE 6. INFLUENCE OF INITIAL EXCITATION PULSE ON DISTANCE-AMPLITUDE CURVE

No. SDH	X (in.)	y (in.)
1	8.5	5.0
2	8.0	4.0
3	7.5	3.0
4	7.0	2.0
5	6.5	1.5
6	6.0	1.25
7	5.5	1.0
8	5.0	0.875
9	4.5	0.750
10	4.0	0.625
11	3.5	0.5
12	3.0	0.375
13	2.5	0.25
14	2.0	0.125
15	1.5	0.062



NOTE: ALL DIMENSIONS IN INCHES (1 in. = 25.4 mm)

FIGURE 7. SIDE-DRILLED HOLE BLOCK

It is therefore apparent that variation in test results is unavoidable unless the initial excitation pulse is controlled within a certain range. As one may already have noticed, the peak to peak amplitude of the initial excitation pulse is usually smaller when it is adjusted to the type-B pulse than when it is adjusted to the type-A pulse. This means that with a receiver of given dynamic range of amplification, the type-A pulse would give a higher overall system sensitivity than the type-B pulse. On the other hand, the type-B pulse would give a better depth resolution than the type-A pulse. Therefore, compromise to an optimum condition is necessary.

For assessing ultrasonic transducer performance, a type-B initial excitation pulse is recommended which has a duration less than or equal to 0.5 μ sec and the shape of a spike or single cycle bipolar spike. Although a thorough evaluation of the effects of initial excitation pulse length and shape on ultrasonic transducer performance was beyond the scope of the present project, the above recommendation is made based upon the following:

- a) Overall system sensitivity does not primarily determine transducer flaw detectability as long as the electrical noise of the system does not exceed the background noise of the material being inspected³. Therefore, some reduction in overall system sensitivity due to the decrease in pulse amplitude associated with adjustment of the instrument to obtain a type-B pulse is of little consequence.
- b) The shorter type-B pulse allows a better determination of transducer depth resolution. In this case, the shortest pulse obtainable is desired since depth resolution improves with shorter pulse lengths. A value of 0.5 μ sec or less was selected since this value is short enough to allow adequate determination of depth resolution and can be obtained for most commercially available instruments.
- c) A spike pulse has a relatively uniform and broad spectrum and thus allows better determination of the transducer operating frequency.

Prior to measuring the ultrasonic transducer performance parameters, therefore, the controls on the ultrasonic instrument should be adjusted using the following procedures:

- (a) Controls on the pulser shall be set as follows. Put a "T" connector on the pulser output of the instrument and connect the transducer to be evaluated to this "T" connector. Then display the initial excitation pulse on an oscilloscope having a bandwidth of 20 MHz or greater by using a 10X or 100X oscilloscope probe which is connected to the other end of the "T" connector as shown in Fig. 8.

By adjusting the pulse length, damping, or tuning controls of the pulser, reduce the duration of the initial excitation pulse to 0.5 μ sec or less. The general shape of the initial excitation pulse shall be either a spike or single cycle bipolar spike (some ripples on the pulse are allowable such as those on the pulses shown in Figs. 3 and 5). While maintaining the duration of the pulse to 0.5 μ sec or less, adjust the controls until a maximum peak-to-peak pulse amplitude is obtained. The adjustment of the duration of the initial excitation pulse can also be accomplished by adding an external

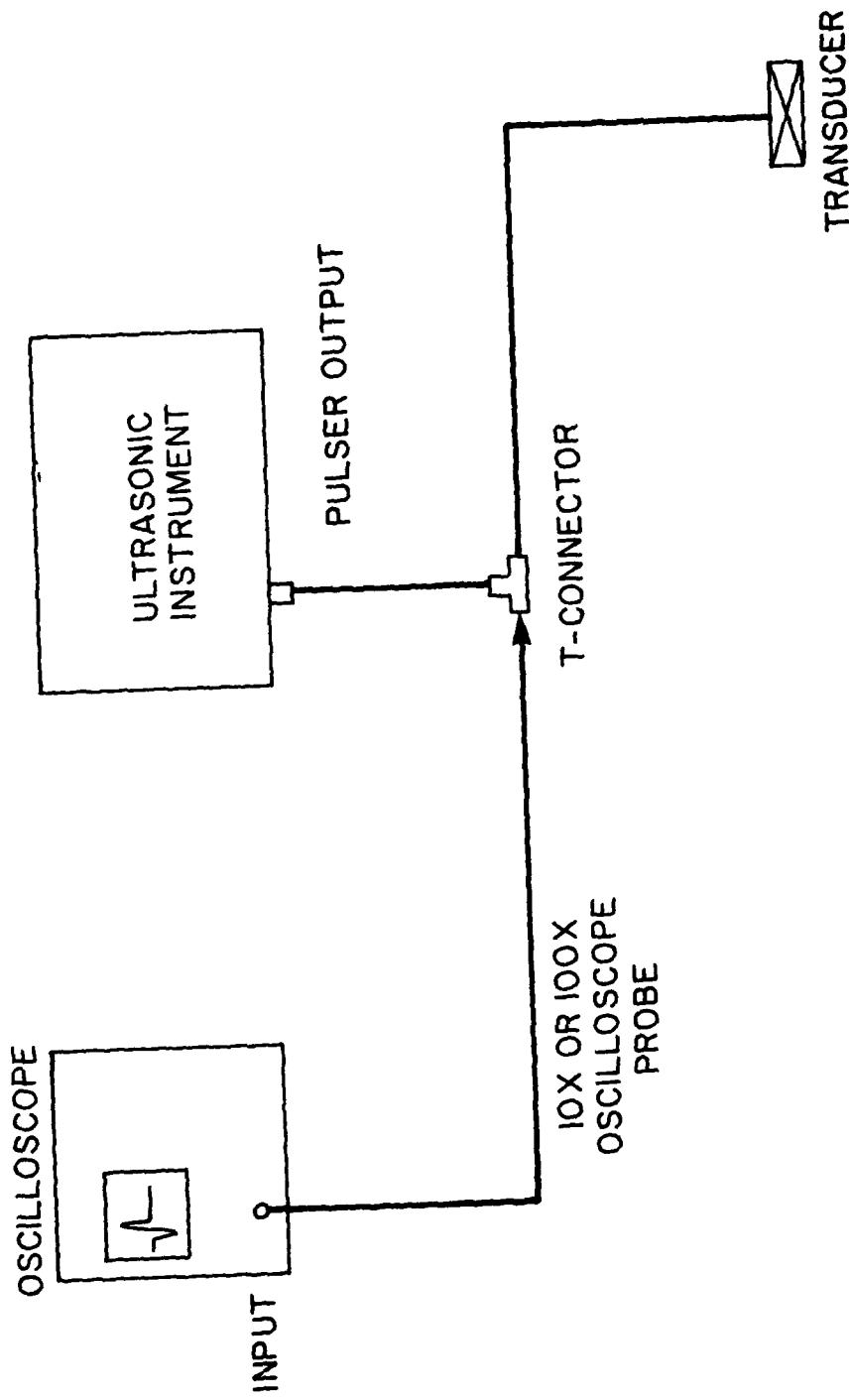


FIGURE 8. BLOCK DIAGRAM FOR MONITORING INITIAL EXCITATION PULSE

resistive load (for example 50 ohm) in parallel with the transducer. An external resistive load is useful when the instrument does not have controls for the output pulse or the adjusted peak-to-peak pulse amplitude is too low (less than 150 V). In the latter case, the peak-to-peak pulse amplitude could be increased by adjusting the pulse length control to the maximum setting and adding the external resistive load in parallel with the transducer. When adjustment of the initial excitation pulse is made, this adjustment should be maintained throughout the measurements described in Section II.B.

Without the use of an oscilloscope, the adjustment of the initial excitation pulse is difficult to achieve. This is because the initial excitation pulse shape displayed on the CRT of the instrument is significantly distorted due to saturation of the receiver amplifier.

- (b) Controls on the receiver should be set as follows:
 - (1) Frequency select control shall be set to the nominal operating frequency of the transducer,
 - (2) Noise suppression control (or "reject" control) shall be set to zero or a minimum,
 - (3) Filter control, if provided, shall be set to the appropriate position so that the ripples in the rectified signal do not exceed 50% of the maximum signal amplitude and the pulse length of the rectified signal does not extend more than 10% of the actual rf-signal pulse length (Section II.A.2 and Fig. 1). Setting the appropriate filter control can be made by following procedures. If a filter control is not provided, the degree of built-in filtering of the instrument must be evaluated using the same procedures described below to determine whether the instrument is appropriate for use in transducer performance evaluation.

First, connect either a 5 or 10 MHz straight beam longitudinal transducer and an oscilloscope probe as shown in Fig. 8.

Second, place the transducer on an aluminum IIW block of Type 1 or Type 2 (from now on designated simply as IIW block) as shown in Fig. 9-a. (Dimensions of the block are indicated in Fig. 9-b.) Obtain rectified video echo signals from the 6 mm deep slot and the adjacent side of the block (reflectors A and B in Fig. 9-a). Adjust the position of the transducer so that the amplitudes of the echoes from these reflectors are approximately the same. Then, by adjusting the receiver gain, set the echo amplitudes to approximately 50% of the full scale of the CRT display.

Third, display the rf-echo signals from these reflectors on the oscilloscope at sweep speeds of 1 or 0.5 μ sec per division (Fig. 10-a). The time interval between the two will be approximately 1.9 μ sec.

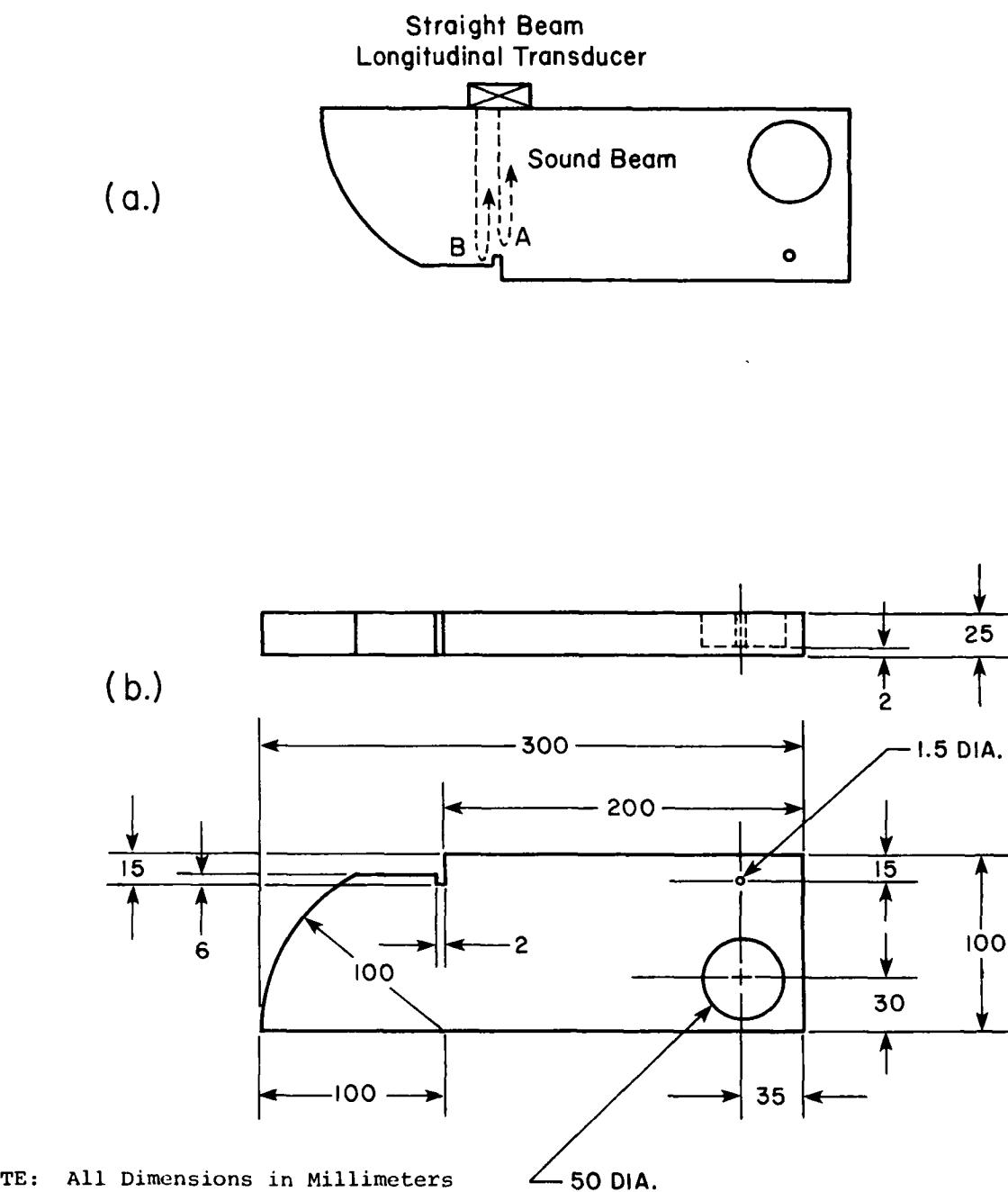


FIGURE 9. IIW BLOCK a) Placement of straight beam longitudinal transducer for time base calibration of display, and b) Dimensions of IIW block - Type 1.

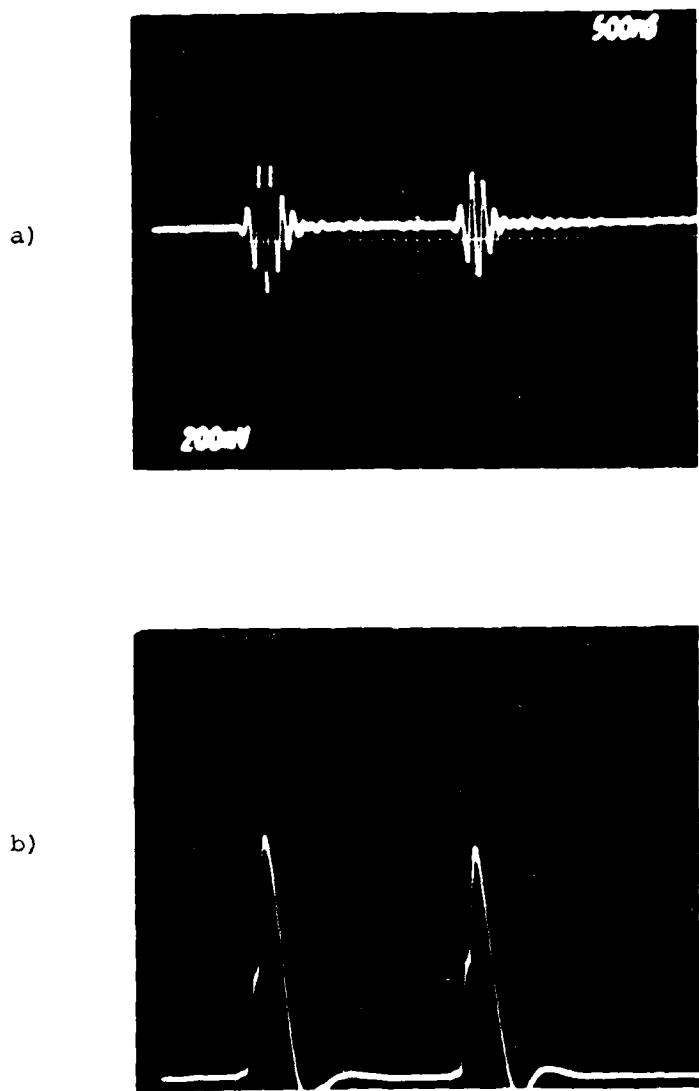


FIGURE 10. CALIBRATION OF ULTRASONIC INSTRUMENT'S TIME BASE
a) RF-echo signals from reflectors A and B (Fig. 9-a)
displayed on oscilloscope (with a 10 MHz straight beam
longitudinal transducer), and b) rectified video signal
displayed on ultrasonic instrument

Fourth, by adjusting the sweep speed and the sweep delay of the CRT display of the ultrasonic instrument, set the leading edges of the rectified echoes to a separation of 1.9 divisions or 3.8 divisions on the CRT display of the instrument (Fig. 10-b). This corresponds to calibrating the CRT display to 1 μ sec per division or 0.5 μ sec per division, respectively.

Fifth, adjust the filter control so that the ripples in the rectified signal do not exceed 50% of the maximum signal amplitude and the pulse length of the rectified signal does not extend more than 10% of the rf-signal pulse length displayed on the oscilloscope. Examples of good and poor filter control adjustments are shown in Fig. 11. In Fig. 11-a, filtering is too low and therefore the ripples in the rectified signal exceed 50% of the maximum amplitude. In Fig. 11-b, filtering is adequate. In Fig. 11-c, filtering is too high and consequently the pulse length of the rectified signal is greater than 110% of the rf-signal pulse length shown in Fig. 11-d.

If the ultrasonic instrument can display both rf and rectified video signals, the use of an oscilloscope is not necessary. In this case, display the rf-echo signals from the two reflectors on the CRT and by adjusting the sweep speed and sweep delay, set the two rf-echo signals apart by 1.9 divisions or 3.8 divisions on the CRT display. Then display rectified video signals and adjust the filter control as described in the fifth step above.

The use of an oscilloscope may be out of the scope of the present Air Force field level NDI activities. However, considering the importance of the initial instrument set-up for minimizing variations in test results, the use of an oscilloscope is considered to be indispensable and should be part of the routine NDI activities.

B. SIMPLIFIED TEST METHODS

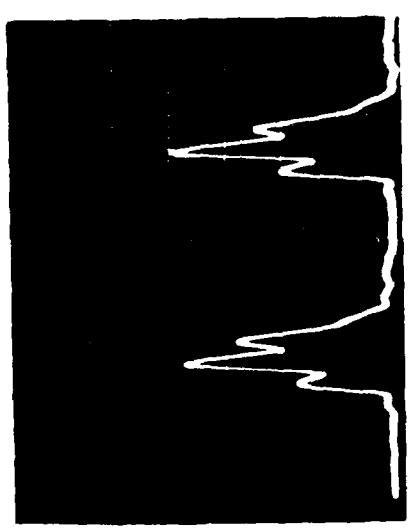
The following simplified test methods apply to both angle beam (usually shear wave) and straight beam (usually longitudinal wave) transducers used in contact with surfaces which are essentially flat. The specifications are primarily intended for procurement of 5 and 10 MHz ultrasonic transducers having piezoelectric elements of 6.35 mm (0.25 in.) diameter (or similar area) routinely used in Air Force NDI. For the case of performance evaluation of in-service transducers, specifications for the transducer wedge misalignment, beam exit point, skew angle, beam angle, and center frequency may be relaxed.

1. Overall Appearance

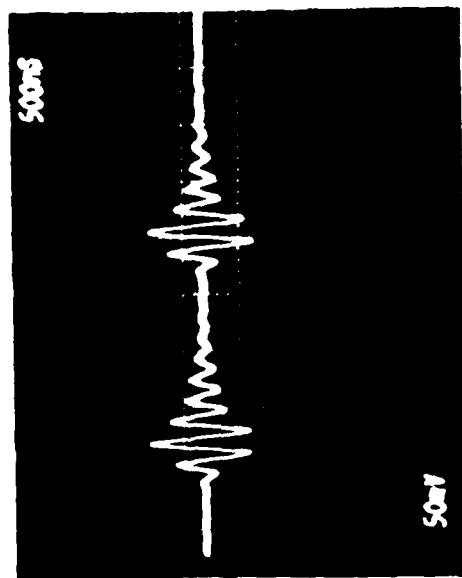
This test is for examination of the overall quality of the transducer appearance.

1.1 Mechanical Damage

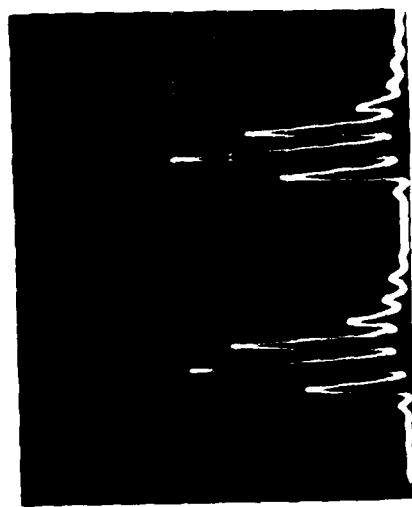
1.1.1 Visually inspect the transducer for any signs of mechanical damage such as dents, pits or severe scratches.



b)



d)



a)



c)

FIGURE 11. EXAMPLES OF RECTIFIED VIDEO SIGNALS (shown in the order of increasing degree of filtering) a) too little filtering, b) adequate filtering, c) too much filtering, and d) actual rf-echo signals displayed on oscilloscope (with a 5 MHz straight beam longitudinal transducer)

1.1.2 No evidence of mechanical damage shall be present.

1.2 Flatness of Contacting Surface

1.2.1 Place a straightedge across the center of the transducer's contacting surface. Hold the transducer and straightedge against a light source and view the arrangement as shown in Fig. 12, keeping the eye at the same level as the transducer's contacting surface. While maintaining the positions of the straightedge and the eye, slowly rotate the transducer 360°. If any areas are found where light shines between the straightedge and the transducer surface, determine if an AWS gauge #44 wire can be inserted. To do this, it may be necessary to hold the transducer in a vice between soft rubber pads.

1.2.2 There shall be no areas where an AWS gauge #44 wire can be inserted between the straightedge and transducer contacting surface, except for the transducer edge chamfer.

1.3 Transducer Wedge Misalignment

1.3.1 Examples of misalignment of the transducer wedge with respect to the transducer case are shown in Fig. 13. For measurement of type a) misalignment in Fig. 13, place a protractor on the contacting surface of the wedge. Set the base line of the protractor parallel with the transducer case and align the center of the protractor's base line to a corner of the wedge as shown in Fig. 14-a. Measure the indicated misalignment angle. For types c) and d) misalignment in Fig. 13, place the transducer and the protractor on a flat surface as shown in Fig. 14-b. Align the center of the protractor's base line to a corner of the transducer case while maintaining the base line of the protractor parallel to the flat surface. Measure the misalignment angle as shown in Fig. 14-b. For type b) centering misalignment, place a graduated scale across the contacting surface of the wedge. Measure distances d_1 and d_2 between the transducer case and the sides of the wedge as shown in Fig. 14-c. The off-center distance is $(d_2 - d_1)/2$.

1.3.2 Misalignment angle with respect to the transducer case shall not exceed 2°. Off-center distance shall not exceed 1 mm.

2. Beam Exit Point (or Index Point)

This test is to determine the position of beam exit from the wedge of angle beam transducers. The beam exit point shall be engraved on each side of the transducer case.

2.1 Place the transducer at the center of the 100 mm radius quadrant of an IIW block as shown in Fig. 15. Keeping the transducer parallel to the edge of the block, adjust the position of the transducer until the echo obtained directly from the 100 mm radius quadrant is maximized. The beam exit point of the transducer corresponds to the engraved line on the block which marks the center of the 100 mm radius quadrant. Mark the beam exit point on the side of the transducer case. Alternatively, any reference block having a concave circular reflector can be used for the beam exit point measurements following the same procedures described above (in this case the 100 mm radius quadrant is replaced by the concave circular reflector).

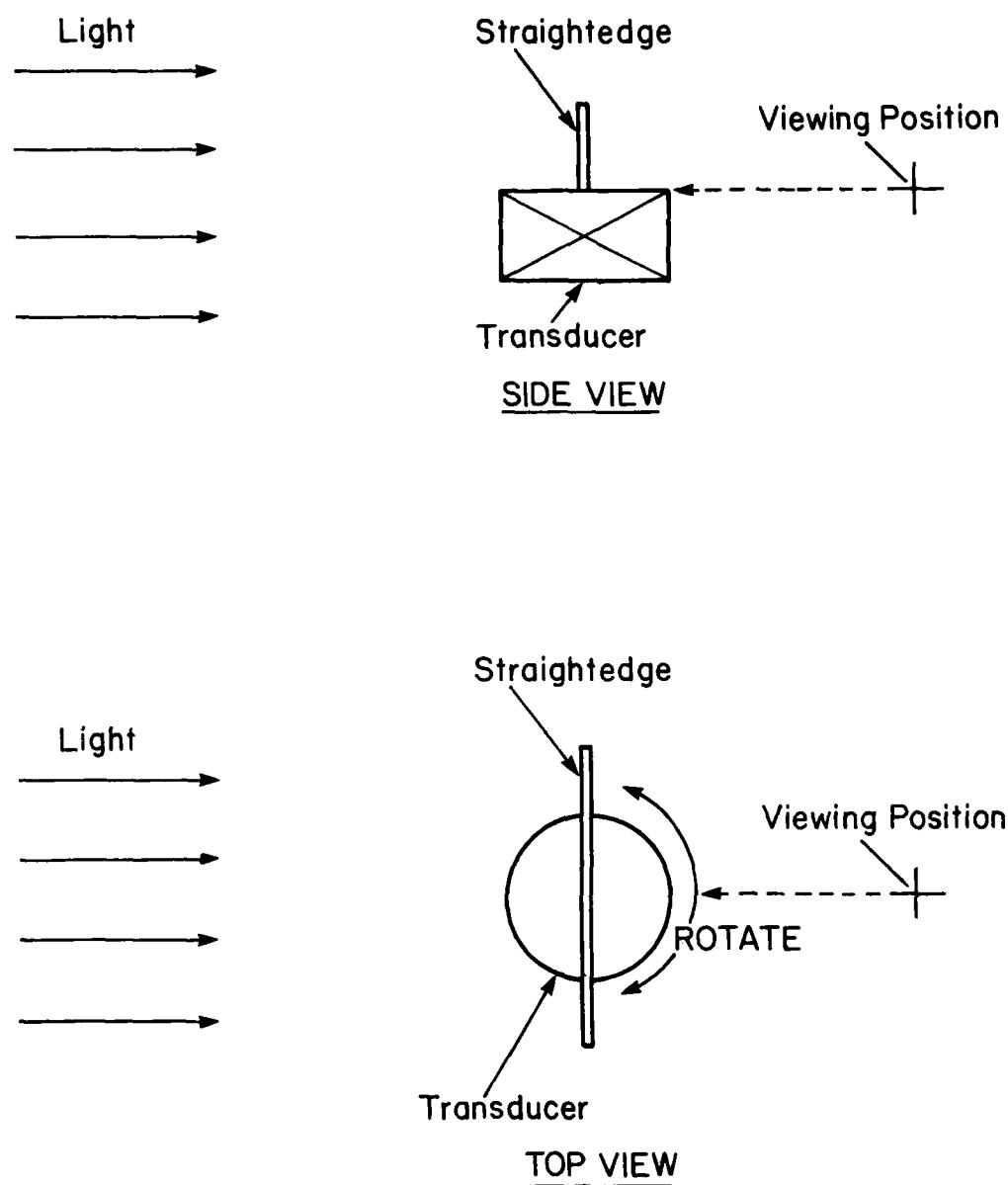


FIGURE 12. CONTACT SURFACE FLATNESS MEASUREMENT

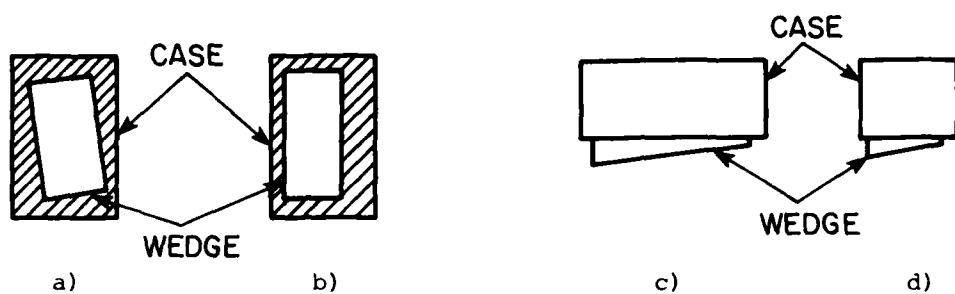


FIGURE 13. EXAMPLES OF TRANSDUCER WEDGE MISALIGNMENT

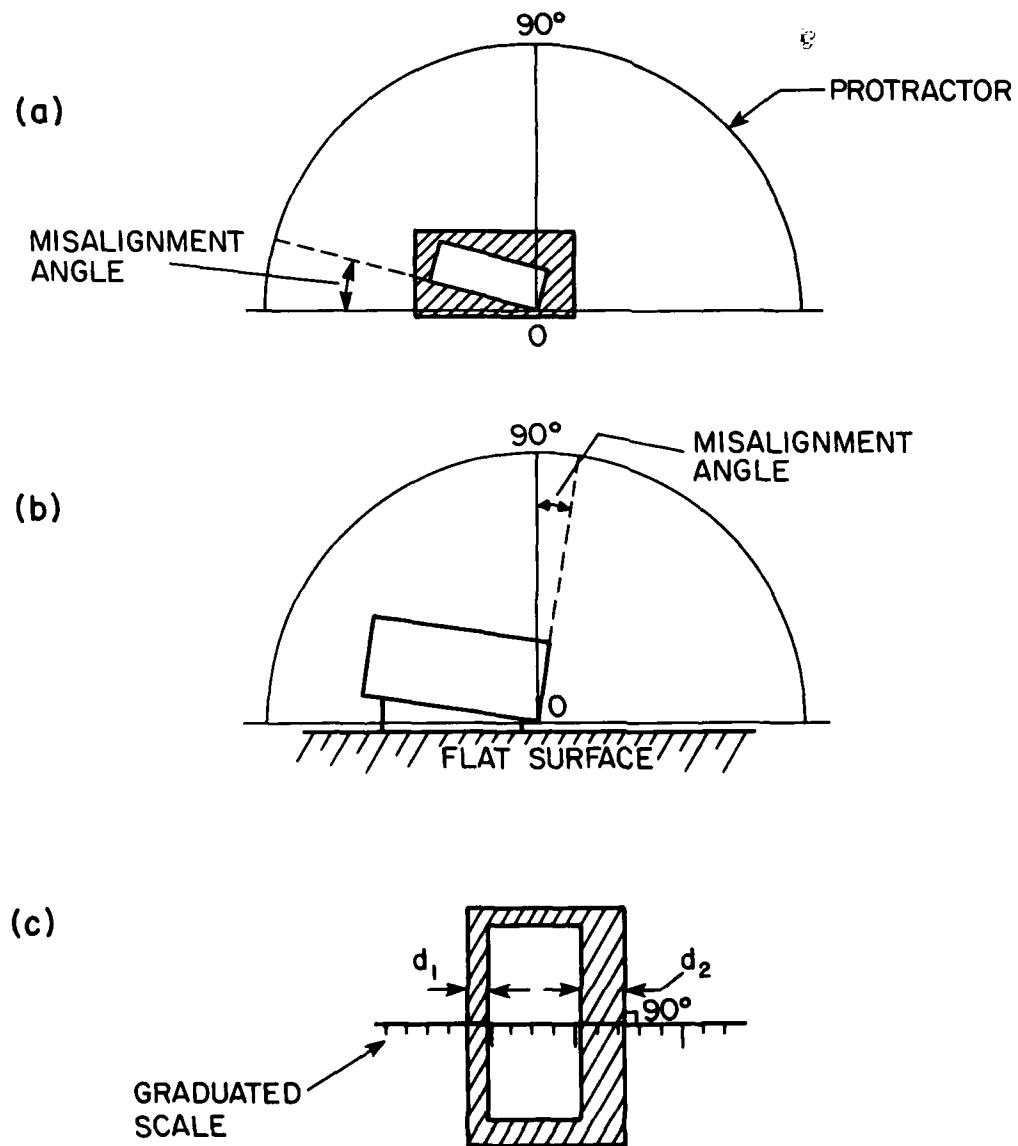


FIGURE 14. TRANSDUCER WEDGE MISALIGNMENT MEASUREMENT
 a) and b) misalignment angle measurement, and
 c) off-center distance measurement

2.2. The measured position of the beam exit point shall be within ± 1 mm of the engraved beam exit point of the transducer.

3. Beam Angle

This test is to determine the angle between the refracted sound beam and the normal to the transducer contacting surface.

3.1 Angle Beam Transducer

3.1.1 Determine the beam exit point of the transducer as described in Clause 2.1. Place the transducer on an IIW block so that a direct echo is obtained from the 50 mm diameter hole as shown in Fig. 16. By moving the transducer back and forth along the side of the block, maximize the echo from the hole. The beam angle is indicated by the position of the measured beam exit point against the scale engraved on the side of the block.

3.1.2 The measured beam angle shall be within $\pm 2^\circ$ of the nominal beam angle of the transducer. The nominal beam angle of the transducer in the test block is obtained from the name-plate beam angle of the transducer by using the following equation

$$\theta_{NT} = \sin^{-1} (V_T \sin \theta_{NP}/V_R)$$

where θ_{NT} is the nominal beam angle in the test block, θ_{NP} is the name-plate beam angle, V_T is the sound velocity in the test block, and V_R is the sound velocity in the material to which the name-plate beam angle is referred. For example, in an aluminum test block, the nominal beam angle of the transducer whose name-plate beam angle is 45° in steel is then

$$\theta_{A1} = \sin^{-1} (V_{A1} \sin 45^\circ/V_{steel}) = 42.7^\circ$$

by taking $V_{A1} = 3.10 \times 10^5$ cm/sec and $V_{steel} = 3.23 \times 10^5$ cm/sec.

3.1.3 Note: The beam angle also depends on the velocity of sound in the wedge of the transducer. Since the sound velocity in the wedge varies with temperature, it is recommended that the beam angle measurement be carried out over a room temperature range (i.e. 15°C to 20°C).

3.2 Straight Beam Transducer

3.2.1 For measuring the beam angle of the straight beam transducer, it is recommended that a test block such as shown in Fig. 17 be used. Place the transducer on side (1) of the block directly above hole A (reference point 0). Position the transducer at the middle of the block thickness. Rotate the transducer continuously through an angle of 90° and determine the orientation of the probe at which the echo from the hole is minimized.* While maintaining this orientation, scan the transducer across the hole until a maximum echo signal is obtained from the hole. The beam angle is indicated by the position of the center of the transducer against the scale engraved on the side of the block.

*This will direct the sound beam through the center portion of the thickness of the block. If the beam is off the normal direction, the echo will be maximum when the beam is directed toward the corner formed by the side drilled hole and a side wall of the block. If the beam is normal to the contacting surface, the amplitude of the echo will remain constant.

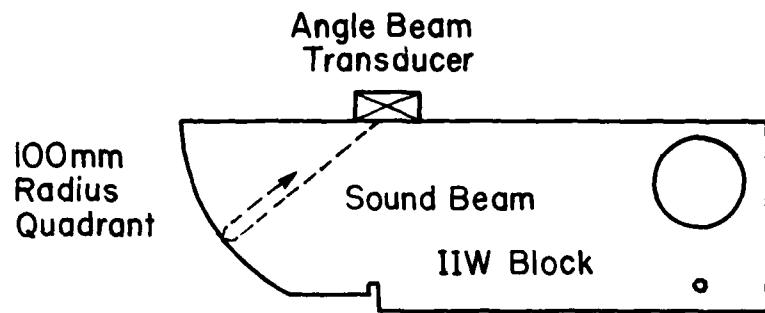


FIGURE 15. BEAM EXIT POINT MEASUREMENT

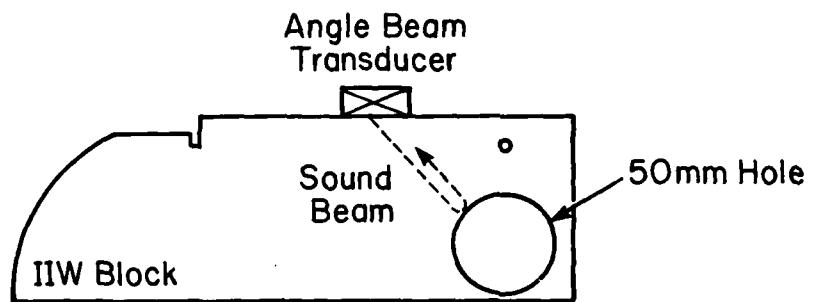


FIGURE 16. BEAM ANGLE MEASUREMENT FOR ANGLE BEAM TRANSDUCER

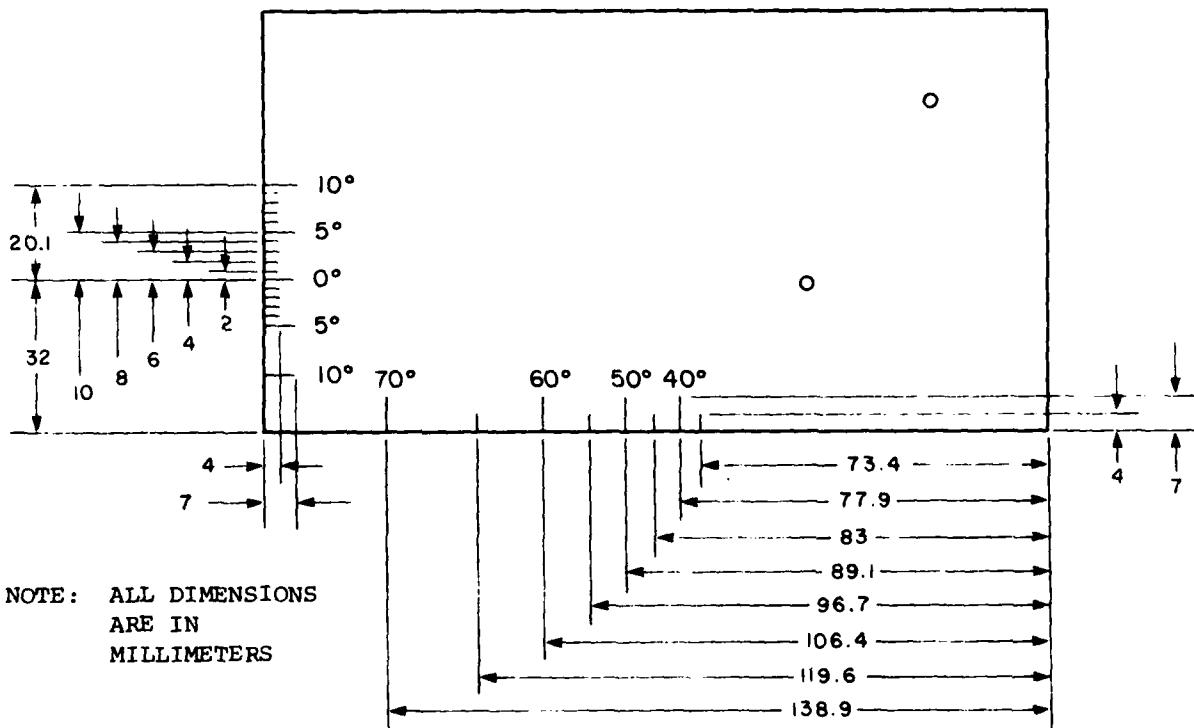
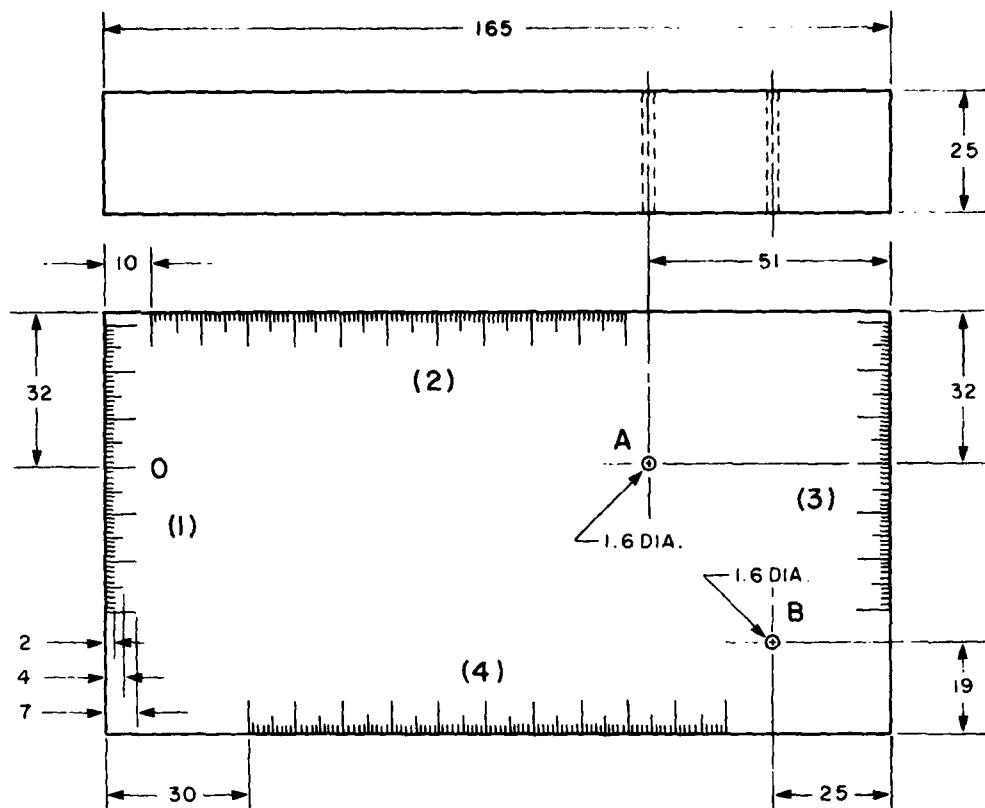


FIGURE 17. TEST BLOCK FOR MEASURING BEAM ANGLE
OF STRAIGHT BEAM TRANSDUCER

3.2.2 The measured beam angle shall not exceed 2°.

4. Skew Angle

This test is to measure the beam misalignment angle of the angle beam transducer with respect to the transducer symmetry axis (Fig. 18).

4.1 Place the IIW block flat on one side and adjust the transducer to maximize the echo from the lower corner of the block (Fig. 19). The corner of the block where there are no scale engravings shall be used. Place a protractor on the block as shown in Fig. 19 and measure the skew angle. Alternatively, any reference block having right angled edges and a constant thickness can be used for the skew angle measurement.

4.2 The measured skew angle shall not exceed 2°.

5. Beam Divergence Angle

This test is to measure the degree of beam divergence which determines the angular resolution of the transducer. Contours of fixed relative sound amplitude (with respect to the maximum sound amplitude of a beam profile at a given distance from the transducer) are shown schematically in Fig. 20. As shown, the beam initially contracts in the near field (which covers the region between the transducer and a distance of approximately $D^2/4\lambda$ where D is the diameter of the piezoelectric element of the transducer and λ is the wavelength of the generated sound) and then diverges in the far field (the region where the distance is greater than $D^2/4\lambda$). Therefore, the beam divergence angle should be measured in the far field of the transducer. The beam divergence angle is given by $\tan^{-1}(BW/2R)$ where BW is the width of the beam at a distance R (Fig. 20). In the following description of the measurements, BW is taken at -6 dB points.

5.1 Straight Beam Transducer

5.1.1 For measuring the beam divergence angle of the transducer, it is recommended that a test block such as shown in Fig. 17 be used. Place the transducer on side (1) of the block and maximize the echo signal from hole A as described in clause 3.2.1. Adjust the receiver gain of the ultrasonic instrument so that echo height reaches 80% of the full scale of the CRT display. Read (or mark) the position of the center of the transducer on the block. While maintaining the transducer's orientation, scan the transducer across hole A in a direction parallel to the edge of the block. When the echo height drops to 40% of the full scale of the CRT display (i.e. -6 dB) on both sides of the maximum response position, read (or mark) the respective positions of the center of the transducer on the block. Then the beam divergence angle is given by $\tan^{-1}(BW/2R)$ where BW is the distance between the two -6 dB amplitude response positions of the transducer on the block and R is the distance between the side drilled hole and the center of the transducer at the maximum response position. Repeat the same procedures with the transducer on side (3) of the block. Average the two values thus obtained.

5.1.2 Beam divergence angle shall not exceed 10% of the theoretical value which is given by $\theta_D = \sin^{-1}(0.7 \lambda/D)$ for the -6 dB beam width where λ is the

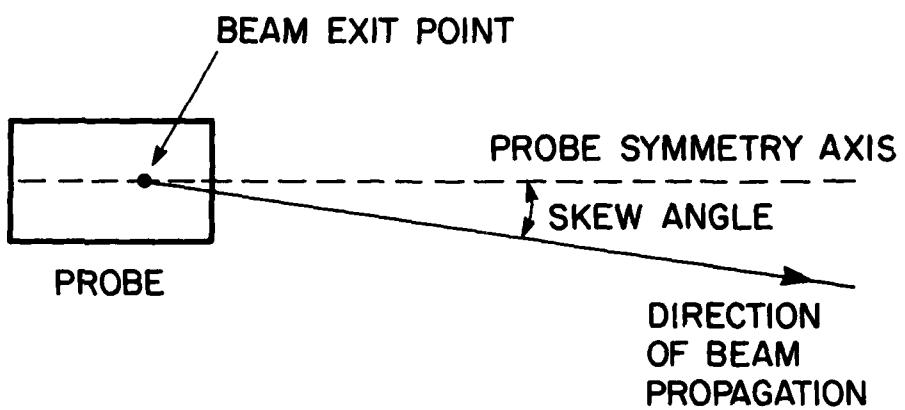


FIGURE 18. BEAM MISALIGNMENT (SKEW ANGLE)

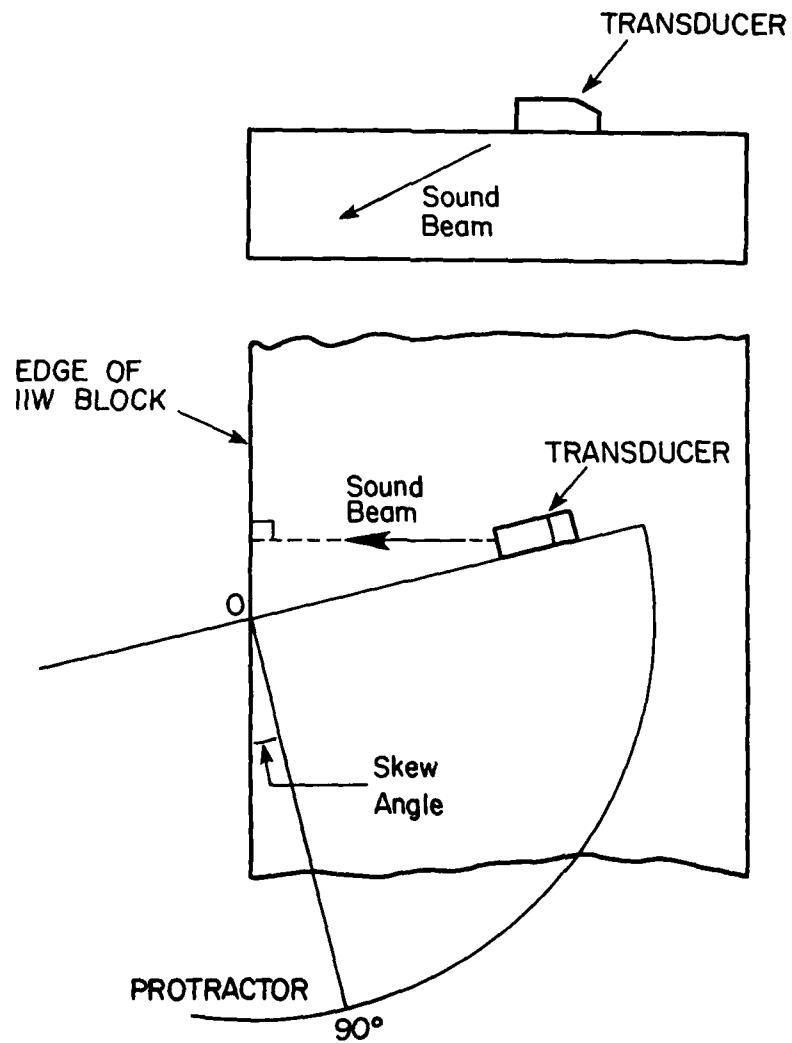


FIGURE 19. SKEW ANGLE MEASUREMENT

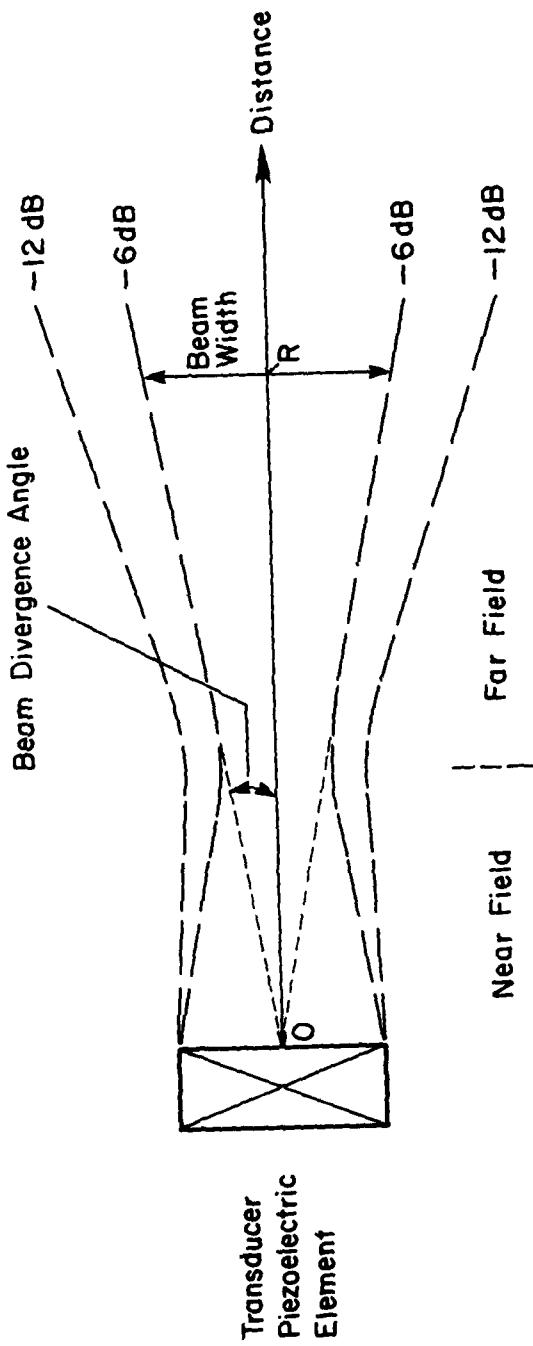


FIGURE 20. SCHEMATIC PRESENTATION OF SOUND BEAM DIVERGENCE

wavelength of the sound at the name-plate frequency of the transducer and D is the name-plate diameter of the piezoelectric element of the transducer. Note that the above equation for theoretical beam divergence angle is for monochromatic and continuous sound wave generation by an ideal piston radiator.)

In aluminum, a 5 MHz longitudinal transducer having a 6.35 mm (0.25 in.) diameter piezoelectric element will have the theoretical beam divergence angle of

$$\begin{aligned}\theta_D &= \sin^{-1} (0.7 \lambda/D) \\ &= \sin^{-1} (0.7 v/fD) \\ &= \sin^{-1} [(0.7 \times 6.35 \times 10^5)/(5 \times 10^6 \times 0.635)] \\ &= 8.05^\circ\end{aligned}$$

where the velocity v of the longitudinal wave in aluminum is taken as 6.35×10^5 cm/sec. If the above quoted transducer is a 10 MHz transducer, then the beam divergence angle will be 4.01° . For values of $\sin^{-1}x$ or $\tan^{-1}x$, see Appendix A.

5.1.3 Example: Suppose the following data are obtained from a straight beam transducer.

R (mm)	X _{max} (mm)	X _{-6 dB} , left (mm)	X _{-6 dB} , right (mm)
113	2	-12	17
50	1	-5	7

where the scale on the left hand side of the reference point 0 on the block (Fig. 17) is taken as negative (-). Then the beam widths are $17 - (-12) = 29$ mm for $R = 113$ mm and $7 - (-5) = 12$ mm for $R = 50$ mm. The average value of the beam divergence angle is then

$$\begin{aligned}\bar{\theta}_D &= (1/2)(\tan^{-1}[29/(2 \times 113)] + \tan^{-1}[12/(2 \times 50)]) \\ &= 7.15^\circ.\end{aligned}$$

5.2 Angle Beam Transducer

5.2.1 Place the transducer on side (2) of the test block shown in Fig. 17. Maximize the echo signal from side-drilled hole A and set the echo height to 80% of the full scale of the CRT display by adjusting the receiver gain of the ultrasonic instrument. Record (or mark) the position of the beam exit point on the block at this maximum response position and measure the beam angle of the transducer in this block. Scan the transducer across the maximum response position keeping the transducer parallel to the edge of the block. When the

echo height drops to 40% of the full scale of the CRT display (i.e. -6 dB) on both sides of the maximum response position, record (or mark) the respective positions of the beam exit point of the transducer on the block. The beam divergence angle is given by $\tan^{-1} (BW \cos \theta / 2R)$ where BW is the distance between the two -6 dB amplitude points on the block, θ is the measured beam angle of the transducer in the block, and R is the distance between the side-drilled hole and the beam exit point of the transducer at the maximum response position. Repeat the same procedures with the probe on side (4) of the block. (For 60° angle beam transducers, use side-drilled hole B.) Average the two values thus obtained.

5.2.2 Beam divergence angle shall not exceed 10% of the theoretical value as described in 5.1.2.

6. Center Frequency

This test determines the operating frequency of the transducer.

6.1 For determining the center frequency of the transducer, use is made of the rf-echo from the 100 mm radius quadrant of the IIW block for angle beam transducers (whose beam exit point should be set to the center of the 100 mm radius quadrant) and the rf-echo from the opposite face of the block at a distance of 100 mm for straight beam transducers (Fig. 21).

If the ultrasonic instrument employed is able to display an rf-echo signal on the CRT, determine the setting of the sweep speed control of the display at which the echoes of a longitudinal wave from the 6 mm deep slot in the IIW block are separated by 1.9 or 3.8 divisions on the CRT display (refer to Fig. 9 and 10). Each division on the CRT display then corresponds to 1 μ sec or 0.5 μ sec, respectively, at this setting.

By using the sweep delay control, display the rf-echo signal from either the 100 mm radius quadrant or the opposite face of the block at the above determined setting of the sweep speed control. Count the number of rf cycles in the pulse length of the rf-echo signal. The center frequency of the transducer in units of MHz corresponds to the number of rf cycles divided by the pulse length (in μ sec).

If the ultrasonic instrument employed does not have rf-echo display, then display the rf-echo signal on an oscilloscope by using a 10X oscilloscope probe as shown in Fig. 8. Count the number of rf cycles and determine the center frequency of the transducer as described above.

6.2 The measured center frequency shall be within 20% (note the change in values from the previous specifications in Phase II report³) of the name-plate frequency of the transducer.

7. Pulse Length

This test is to measure the duration of the rf-echo signal of the generated sound beam. Pulse length is defined as the time interval over which the amplitude of the pulse envelope exceeds 10% of its maximum amplitude (Fig. 22). The pulse envelope represents the contour of the rf-echo signal cycles. The depth resolution capability of a transducer is determined by the pulse length.

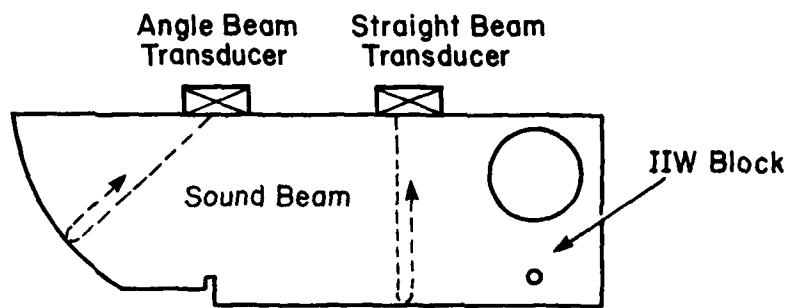


FIGURE 21. PLACEMENT OF TRANSDUCERS FOR OBTAINING REFERENCE BACK WALL ECHO

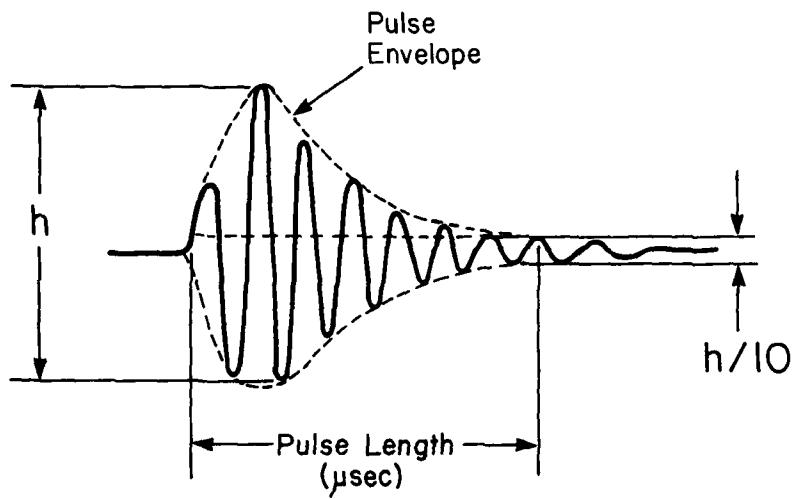


FIGURE 22. PULSE LENGTH MEASUREMENT

7.1 Display the rf-echoes obtained from either the 100 mm radius quadrant of the IIW block (for angle beam transducers) or the opposite face of the block at a distance of 100 mm (for straight beam transducers) on the CRT display of the ultrasonic instrument at the predetermined setting of the sweep speed control of the display as described in Clause 6.1. Then measure the pulse length as defined above. If the ultrasonic instrument does not have rf-echo display, measure the pulse length of the rectified video echo signal by using the same definition given above. (In this case, the setting of the sweep speed control is made by using the rectified video echo signals from the 6 mm deep slot in the IIW block.)

7.2 The measured pulse length shall not exceed 1.5 μ sec.

8. Dead Zone

This test measures the duration of time immediately after applying the initial excitation pulse to the transducer, during which it is not possible to detect small flaws with certainty.

8.1 Straight Beam Transducer

8.1.1 Place the transducer on the IIW block as shown in Fig. 20 and maximize the echo from the opposite face. Adjust the receiver gain control so that the echo height is 50% of the full scale of the CRT display. Set the sweep speed control of the display as described in Clause 6.1 by using the echoes from the 6 mm deep slot in the IIW block. Increase the receiver gain by 20 dB and measure the time interval between the initial rise of the excitation pulse and the instant at which the amplitude of the excitation pulse tail or internal noise decreases to 25% of the full scale (Fig. 23).

8.1.2 The time interval (dead zone) shall not exceed 2.5 μ sec.

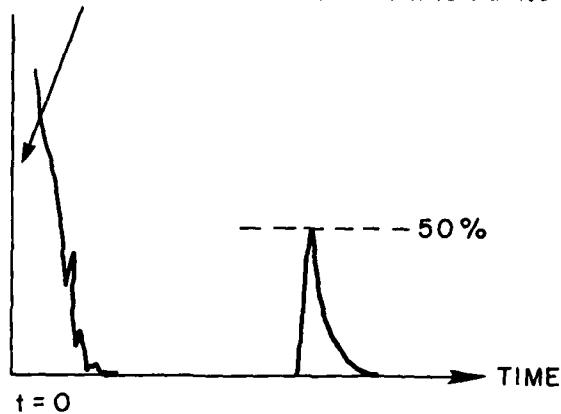
8.2 Angle Beam Transducer

8.2.1 Place the transducer on the IIW block and maximize the echo from the 100 mm quadrant. Follow the same procedures described in Clause 8.1.1 with the following modification: for 5 MHz transducers increase the receiver gain by 30 dB (note the change in values from the previous specifications in Phase II report³), and for 10 MHz transducers, increase the receiver gain by 40 dB.

Measure the ultrasonic wave travel time in the transducer wedge (round trip) as follows: first, remove the transducer from the IIW block and remove the couplant; second, remove and replace a finger tip on the bottom of the wedge where beam exit point is located and observe the fluctuation in the initial excitation pulse and internal noise; and third, measure the time between the initial rise of the excitation pulse and the beginning point of the fluctuation. (To see the fluctuation more clearly, increase the receiver gain.) For more accurate measurement of the elapsed time, refer to Appendix B.

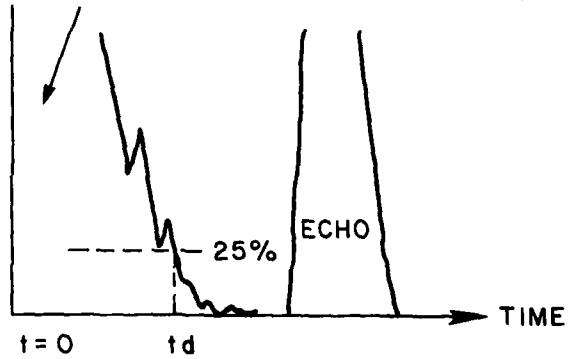
8.2.2 The difference between the time interval (from the initial rise of the excitation pulse to the instant at which the amplitude of the excitation pulse tail or internal noise decreases to 25% of the full scale) and the elapsed time in the transducer wedge shall not exceed 4 μ sec.

Initial Excitation Pulse and Internal Noise



- a) Maximize echo from the opposite surface of the IIW block and adjust the gain control until the echo height reaches 50% of full scale

Initial Excitation Pulse and Internal Noise



- b) Increase the gain by prescribed amount. Then measure t_d at which excitation pulse tail amplitude becomes 25% of full scale.

FIGURE 23. DEAD ZONE MEASUREMENT

9. Signal-to-Noise Ratio

This test determines the flaw detectability of the transducer.

9.1 Place the transducer on the IIW block as shown in Fig. 21. Maximize the echo from either the 100 mm radius quadrant (for angle beam transducers) or the opposite face (for straight beam transducers). With the leading edge of the initial excitation pulse positioned at the left edge of the CRT display, position the echo at 60% of the full horizontal scale by adjusting the sweep speed control. Increase the receiver gain until the maximum noise level within the range of 10% to 60% of the horizontal scale reaches 25% of the full vertical scale of the CRT display. Note the gain reading. If the noise height does not reach 25% of the full vertical scale at the maximum receiver gain, then note the height of the noise. Readjust the receiver gain so that the above echo signal height reaches either 25% of the full vertical scale or the noise height at the maximum receiver gain. The difference in gain between the two cases is the signal-to-noise ratio (in dB) of the transducer.

9.2 The signal-to-noise ratio shall be at least 50 dB.

10. Overall System Sensitivity

This test determines the sensitivity of the combined system of the ultrasonic instrument and the transducer.

10.1 Place the transducer on the IIW block as shown in Fig. 21. Maximize the echoes either from the 100 mm radius quadrant (for angle beam transducers) or from the opposite face (for straight beam transducers). Set the echo height to 25% of the full scale of the CRT display by adjusting the receiver gain. Read the remaining receiver gain still available.

10.2 The remaining receiver gain shall be at least 40 dB.

III. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

In this project, simplified test methods for assessing performance parameters of 5 and 10 MHz contact type ultrasonic transducers for Air Force field and depot use were developed. From the results of previous investigations³, the following ten ultrasonic transducer performance parameters were considered: Overall Appearance, Beam Exit Point, Beam Angle, Skew Angle, Beam Divergence Angle, Center Frequency, Pulse Length, Dead Zone, Signal-to-Noise Ratio, and Overall System Sensitivity.

Requirements for ultrasonic instruments to be used in tests are described. Due to the effect of interaction between the ultrasonic instrument and the transducer, the shape of the initial excitation pulse applied to the transducer varies. The influence of initial excitation pulse variation on the transducer performance was demonstrated. Since the effect of interactions varies depending on the control settings of a given ultrasonic instrument, it is emphasized that the initial excitation pulse applied to the transducer should be controlled to a certain specified condition such as a spike or single cycle bipolar spike with duration less than 0.5 μ sec. Such practices of controlling the initial excitation pulse minimize variations in test results due to different instrument control settings and contribute to more uniform and instrumentally unbiased test results. Methods of establishing a specified initial excitation pulse by, for instance, adjusting controls on the ultrasonic instrument are described. The use of an oscilloscope was found necessary to monitor the initial excitation pulse. Adjustment of the initial excitation pulse to a specified condition should precede the testing of each transducer's performance parameters.

B. RECOMMENDATIONS

It has been shown that the performance of a transducer varies depending on the shape of the initial excitation pulse which is influenced by interactions between the ultrasonic instrument and the transducer. In order to more precisely specify a range of initial excitation pulse lengths and shapes than was possible in this project, a thorough investigation of the influence of the initial excitation pulse length and shape on transducer performance is necessary.

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2. V. D. Smith, C. M. Teller and R. K. Swanson, Final Report on SwRI Project No. 15-5024 (Contract No. F41608-77-C-1381), "Engineering Services to Determine Acceptance Limits of Ultrasonic Transducers for Nondestructive Inspection", June 1978.
3. H. Kwun, G. L. Burkhardt and C. M. Teller, Final Report on SwRI Project No. 15-5468 (Contract No. F41601-78-C-1823), "Ultrasonic Transducer Performance Requirements - Phase II", August 1981.
4. E. P. Papadakis and K. A. Fowler, J. Acoust. Soc. Am. 50, 729 (1971).

APPENDIX A. TABLE OF $\tan^{-1}x$ AND $\sin^{-1}x$

x	$\tan^{-1}x$ (degrees)	$\sin^{-1}x$ (degrees)	x	$\tan^{-1}x$ (degrees)	$\sin^{-1}x$ (degrees)
0	0	0	0.16	9.090	9.207
0.01	0.573	0.573	0.17	9.648	9.788
0.02	1.146	1.146	0.18	10.20	10.37
0.03	1.718	1.719	0.19	10.76	10.95
0.04	2.291	2.292	0.20	11.31	11.54
0.05	2.862	2.866	0.21	11.86	12.12
0.06	3.434	3.440	0.22	12.41	12.71
0.07	4.004	4.014	0.23	12.95	13.30
0.08	4.574	4.589	0.24	13.50	13.89
0.09	5.143	5.164	0.25	14.04	14.48
0.10	5.711	5.739	0.26	14.57	15.07
0.11	6.277	6.315	0.27	15.11	15.66
0.12	6.843	6.892	0.28	15.64	16.26
0.13	7.407	7.470	0.29	16.17	16.86
0.14	7.970	8.048	0.30	16.70	17.46
0.15	8.531	8.627			

APPENDIX B

METHOD OF ELAPSED TIME MEASUREMENT IN THE TRANSDUCER WEDGE
(FOR ANGLE BEAM TRANSDUCERS)

A semi-circle block as shown in Fig. B-1, which is similar to AWS (American Welding Society) type DC (Distance Calibration) block, is required for the elapsed time measurement. Place the transducer near the center of the circle (point 0 in Fig. A). Adjust the transducer back and forth in a direction parallel to the edge of the block and maximize the first returned echo from the radial surface of the block. (Beam Exit point of the transducer should be at the point 0 on the block.) Display an echo pattern as shown in Fig. B-2 on the CRT of the ultrasonic instrument. Measure time (or equivalently distance) T_1 , T_2-T_1 , T_5-T_3 , and then take the average of these values (which is denoted by T_a). Also measure T_3-T_1 , T_5-T_3 , and then take the average of these values (which is denoted by T_b). The round trip time elapsed in the transducer wedge is then given by T_a-T_b . Time calibration of the horizontal axis of the CRT display can be easily performed from the known velocity of sound (V) in the block and the known diameter (D) of the block. If T_b is equal to N divisions of the horizontal axis, each horizontal division corresponds to $2D/(VN)$ seconds.

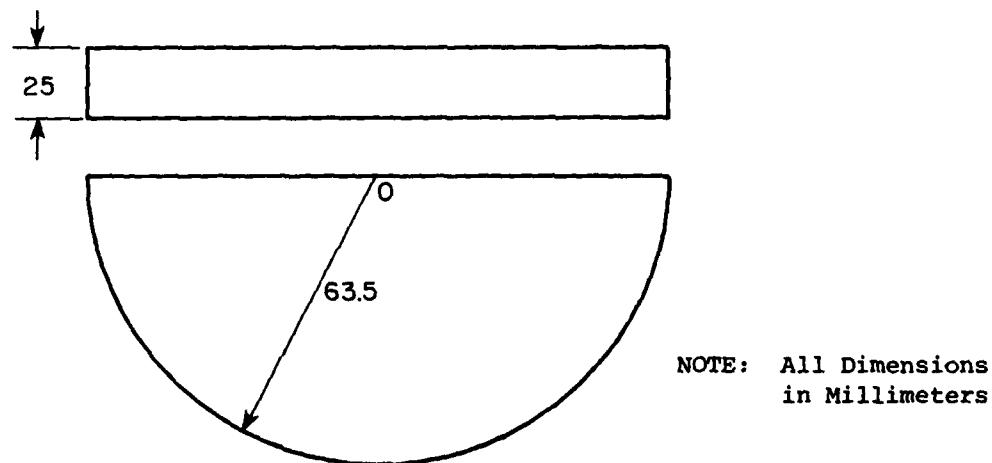


FIGURE B-1. SEMI-CIRCLE BLOCK

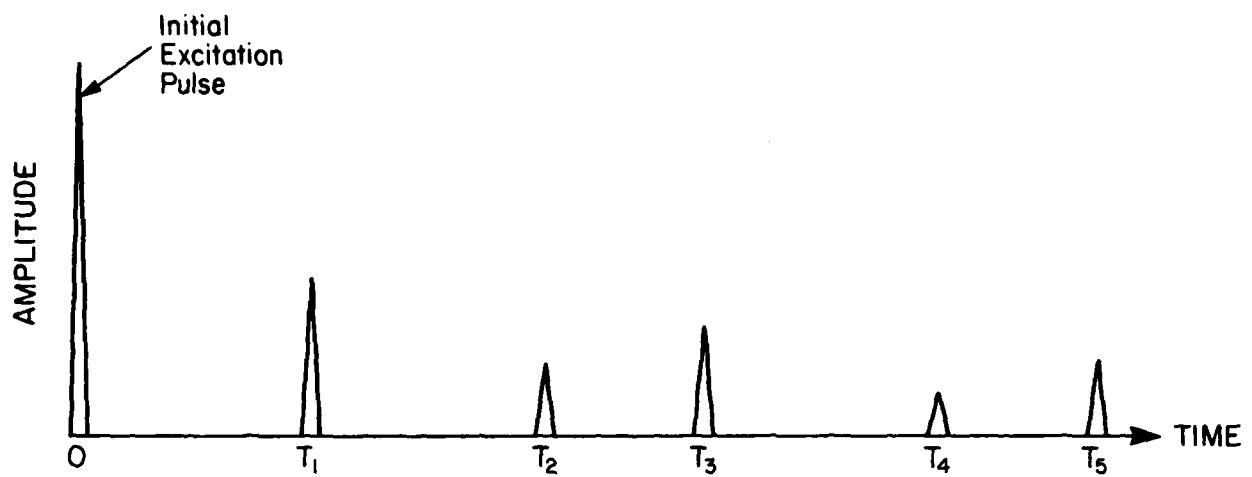


FIGURE B-2. EXAMPLES OF CRT DISPLAY OF ECHOES

** The echoes shown in Fig. B-2 travel the following paths:

ECHO AT TIME	PATH
T_1	$L_3 + 2L_1 + L_3$
T_2	$2(L_3 + 2L_1 + L_3)$
T_3	$L_3 + 2L_1 + 2L_2 + 2L_1 + L_3$
T_4	$L_3 + 2L_1 + 2L_2 + 2L_1 + 2L_3 + 2L_1 + L_3$
T_5	$L_3 + 2L_1 + 2L_2 + 2L_1 + 2L_2 + 2L_1 + L_3$

